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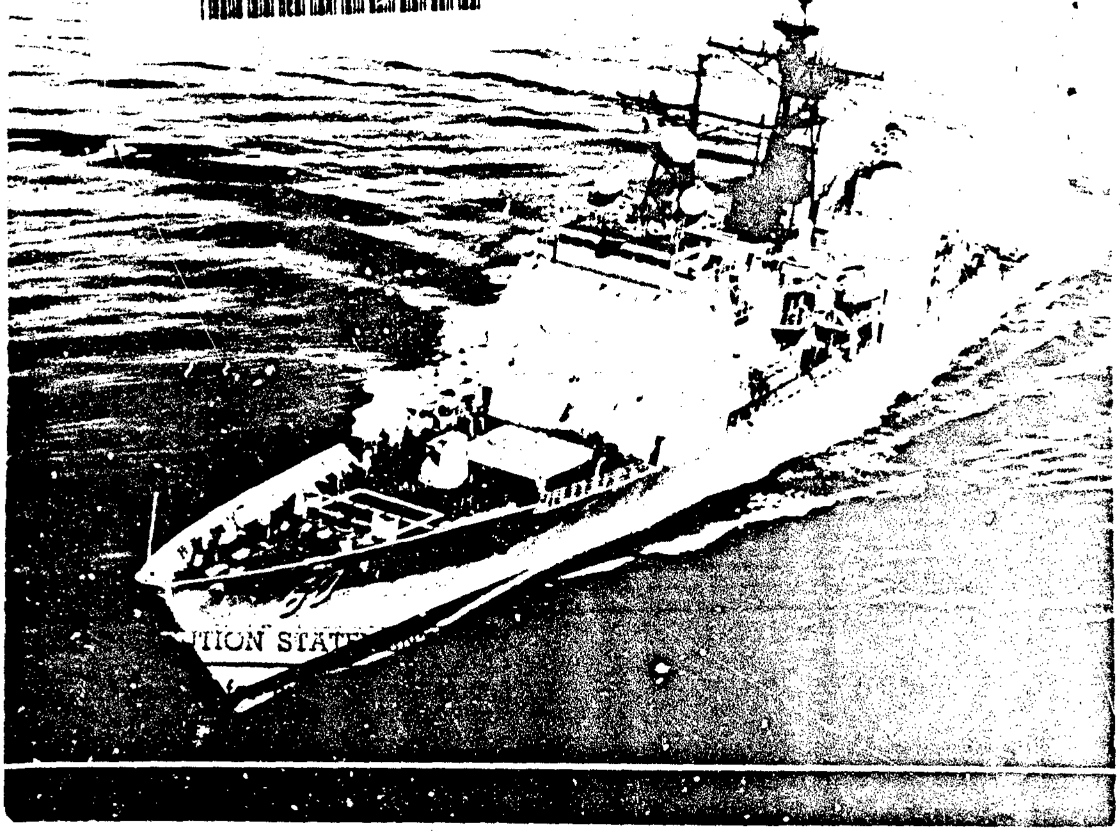

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Damage Control: Automated ship survivability systems, and M-Class Frigate damage control management.
Machinery monitoring and Control Systems: Concept for fiber optic based data acquisition system, concept for marine gas turbine digi monitoring and control, and direction of Royal Navy machinery cont and surveillance systems.
Steering and Stabilization Control: Adaptive rudder roll stabilization control, adaptive steering control, high maneuverability rudder experience, a rudder linguistic self-organizing controller, rudder and fin integrated control, whole sh platform stabilization control, and future French nuclear aircraft carrier stabilization and manoeuvering.

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VOLUME 1

TABLE OF CONTENTS

VOLUME 1

TABLE OF CONTENTS

FUTURE U.S. NAVY CONTROL AND MONITORING SYSTEM DEVELOPMENT

by J. Moschopoulos
Naval Sea Systems Command (USA)
and H. Robey
David Taylor Research Center (USA)

1. ABSTRACT

Decision makers on a modern warship will be required to collect, interpret, and act upon a multitude of data in real-time. The capability to integrate the functional areas of ship machinery control, damage control management, and condition based maintenance monitoring systems addresses several areas that have been documented in the Ship Operational Characteristics Study (SOCS) as "imperative characteristics" for the 2010 combatant. An advanced Machinery Control and Monitoring System (MCMS) will provide this capability in a system that is reliable, robust (damage and fault tolerant), and makes efficient use of manpower resources. The MCMS will integrate the sensing, transmission, interpretation and display of Hull, Mechanical and Electrical (HM&E) parameters necessary for machinery control, condition monitoring, and damage control management. It also provides the interface for the machinery controls with the ship control and combat systems, thereby moving towards a truly Integrated Platform Management System. The system architecture will be highly distributed with the majority of data processing performed at the local level and then passed to the central control consoles. Fiber optic sensors will be used to the maximum extent possible and, where feasible, sensors will be embedded in equipment and made "smart". Distributed microprocessor-based, digital control technology will be used in conjunction with fiber optic data transmission networks to process, transmit, and display sensor inputs. Information management technologies including expert systems/artificial intelligence and data base management will be incorporated in data processing and display to provide decision-making aids to the watch-standers. Standard man-machine interface (MMI) consoles with microprocessor based, high resolution displays will be strategically located to maximize survivability. In general, redundant sensors, processors, data transmission paths, and MMI consoles in combination with the distributed architecture will provide a highly reliable and survivable system. Support of such a highly distributed, software intensive system will be a challenge requiring a high level of hardware fault detection and modular, transportable software.

2. INTRODUCTION

The U.S. Navy's commitment to major new initiatives such as Integrated Electric Drive (IED) and its associated cluster of technologies includes an advanced MCMS which provides for integration of the machinery subsystems/components as well as for interface of the machinery system to the ship and combat system controls. These initiatives provide an unprecedented opportunity for machinery control system Research and Development (R&D) in parallel with the machinery developments prior to ship design and construction. This is in contrast to the present practice of "add-on" supervisory controls during ship design and construction, and "fix-it" R&D programs implemented after the ship is operational. This parallel development approach permits consideration of emerging control and monitoring technology guided by a systems engineering philosophy that exploits any machinery system/control system synergisms.

2.1 What is it?

The advanced MCMS (Figure 1.) will integrate the sensing, transmission, interpretation and display of HM&E parameters necessary for machinery control, condition monitoring and damage control management. It will also provide the means for integration of the machinery system with the ship combat and control systems such that it can communicate status and capabilities to the ship operators and then direct the data in support of mission priorities, all in real-time. This will require rapid reconfiguration capability both in the machinery system and the MCMS. Condition monitoring of vital equipment will support real-time readiness assessment as well as a condition-based maintenance philosophy for selected machinery systems. Monitoring of machinery vibrations and the ability to reconfigure the machinery system provides the means to control machinery noise signature.

An enormous amount of information will be required to provide the desired monitoring and control capabilities. This dictates the use of durable, reliable, low maintenance, low cost sensors. By the nature of the machinery system, the MCMS will be highly distributed, taking advantage of microprocessor technology to process most data and accomplish most dedicated control functions at the local level and transmitting the information to the central control consoles which process common algorithms and perform supervisory duties. This requires a highly reliable and survivable data transmission network. Presentation of all this information must be done efficiently and in a way that supports rapid decision making and response by the operators. Operator proficiency and readiness will be enhanced by providing on-board training, and by use of standardized MMI consoles whose function

can be defined by the software configuration selected by the operator. Since the intent of the MCMS is to reduce the operating and maintenance burden of the machinery system, the MCMS itself must be easily learned and maintained. Detection, isolation and annunciation of MCMS hardware faults will be automatic with isolation to the line-replaceable unit level. Software will be modular and transportable between processors with different architectures.

2.2 Why do we need it?

The Naval Research Advisory Committee (NRAC) Report on "Automation of Ship Systems and Equipment" concludes that -

"The benefit of automation and a machinery control system integrated with a ship's combat and control systems will be a surface combatant that can meet the 21st century threat."

The NRAC panel which produced this report was established in response to the recommendations of the Ship Operational Characteristics Study (SOCS) regarding the need for automation technology to achieve the operational characteristics that must be incorporated in the surface combatant of the 2010 timeframe. Figure 2. identifies the SOCS twelve "imperative characteristics" and further indicates those which are directly impacted by the advanced MCMS. Primary focus is on the two highest priority areas, namely Integrated Machinery Systems and Survivability/Ability to Fight Hurt. Improved survivability can be achieved via redundancy and local control architecture, reconfigurability, and reduced signatures. Enhanced readiness results from real-time monitoring of equipment health and incorporation of embedded training for operators. Operator effectiveness and condition monitoring reduce manpower requirements for operation and maintenance of the machinery system.

The transition from the present Navy control systems to the advanced MCMS, although full of obstacles and critical decision phases, promises to find both the Navy and industry ready to meet the challenge. This optimism is derived from the fact that several characteristics of the advanced MCMS are incorporated in the latest Navy ship designs. Digital computer based controls, designed around linear data buses for distributed processing, are incorporated on the DDG-51 and MHC-51 classes of ships (see Figure 3). In addition, plasma or CRT displays that replaced the majority of the analog read-outs in consoles and limited trending for failure detection are also part of the controls design in these ships. The Navy is also currently looking into the areas of Fiber Optic data transmission and sensing, as well as monitoring systems for condition-based maintenance. It is evident that the

right direction is being pursued although the important, missing element is the integration of all the advanced technologies and concepts towards a Shipwide Platform Management System that encompasses both HM&E and combat systems.

3. DEVELOPMENT APPROACH

Concurrent development of the machinery system and the MCMS permits a parallel approach for the latter which addresses both the implementation technology and the control strategies as well as their interdependencies. The control strategies employed place performance requirements on the system that drive the selection of technology. Conversely, the availability of advanced technology provides opportunities for novel control strategies.

3.1 Control Strategies

The Navy's new initiatives such as the IED machinery cluster are introducing new machinery with different dynamics, similar to, if not greater than, those associated with the change from steam to gas turbines. Lessons learned in the evolution of propulsion system controls for gas turbine/CRP propeller powered ships will be applied in gaining an understanding of the overall system dynamics. The integrated nature of the machinery system requires rethinking of how we should approach component/subsystem controls as well as supervisory level controls.

For example, the gas turbine controls can no longer be designed for a predetermined propulsion power/speed load profile since they will be providing ship service power (a very dynamic load) in addition to an electric propulsion power demand that is not necessarily tied to a particular engine speed. The IED also provides the opportunity for redirection of propulsion power for future combat systems, requiring management of these large amounts of electrical power. The capability to rapidly reconfigure around battle damage to continue fighting will drive the development of control algorithms for detecting/assessing damage or failures and determining the system response. Control strategies must also be developed to incorporate the ability to determine machinery condition, and for utilizing machinery vibration and other data in signature management.

3.2 Implementation Technology

Successful implementation of these control and monitoring capabilities will require a number of rapidly emerging technologies. The biggest challenge will be to evolve a system that can readily incorporate the latest technology as it becomes available without a major redesign.

a. Fiber Optics: High speed fiber optic data networks with the added potential to transmit audio and video data provide the ability to operate in severe environments and the reduced cable size and weight permits physical redundancy without major ship impact - both of these contribute to enhanced survivability and reliability. There are, however, performance tradeoffs which must be examined to ensure the best overall system. Fiber optic sensor technology provides potential for size, weight and cost reductions that will make sensor redundancy feasible. Increased sensor reliability and survivability is also anticipated. Fiber optic sensors would also eliminate Electromagnetic Interference (EMI), electrical shorts, and grounding problems.

b. Smart and Embedded Sensors: In addition to fiber optics, smart sensors capable of self calibration and loss detection will be addressed. Embedded sensors can also be considered with concurrent development of the machinery and controls. Emphasis will be placed on special sensors that can provide early failure detection (failure prognosis) in support of the condition based maintenance concept.

c. Distributed Microprocessors: The level of hardware and software distribution must be addressed with tradeoffs of function/performance versus reliability/survivability. Several generations of this technology will have passed during the R&D program. The impact of emerging open system architecture concepts on the ease of incorporating new processor technology as it evolves needs to be addressed.

Ada, the Department of Defense (D.O.D.) mandated programming language has definite advantages that position her as a strong candidate of the MCMS standard software: portability, reliability due to the extensive compile-time and run-time checking features built into the language etc.

Standard Electronic Modules (SEMs), based on advanced commercial microprocessors, provide an attractive approach towards hardware standardization, which in turn, coupled with standardized software has the potential to be the most cost effective way to address life cycle support demands.

d. AI/Expert Systems: The damage or casualty reconfiguration controls, the machinery condition monitoring system and on-board training are likely candidates for application of expert system technology. Also, this technology can be applied to the managing of presentation of information to the operator, aiding in the decision-making and response, tailoring the presentation such that the operator is focused on the most critical items. In order to properly integrate this technology into the MCMS, it must be embedded in the system software, not run as a stand-alone system

that accesses the MCMS.

e. High Resolution Displays: Automation of HM&E controls and damage control management will require greatly enhanced displays to efficiently present information to a fewer number of operators.

Application of the latest technology in the implementation of the advanced machinery control and monitoring strategies will result in an advanced MCMS which is part of a shipwide Integrated Platform Management System and is:

highly automated	- minimize the manpower necessary to operate and maintain the machinery system and MCMS
fault & damage tolerant	- ensure the available machinery capability is responsive to combat system needs; high level of hardware fault detection
standardized	- hardware and software within the HM&E systems and across ship classes; based on industry standards where feasible; modular, transportable software

4. DEVELOPMENT PLAN

The target for the advanced MCMS is the Battle Force Combatant (BFC) which based on an Initial Operational Capability (IOC) of 2010 requires the ship design process to begin much earlier. To support this schedule, the MCMS must be fully demonstrated in advance, and where possible with actual propulsion machinery. Proper system and component level specifications can not be ensured without a demonstration phase which addresses the critical functions and technologies. Utilization of commercial grade hardware and tailored military software specifications will maximize the demonstration system performance for the available R&D dollars.

Use of industrial standards and open architectures will also provide maximum system flexibility as a prototyping facility for future generations of technology.

Figure 4. illustrates the proposed demonstration system configuration. The intent is to incorporate the entire chain of elements from sensors/actuators to man-machine interface consoles. The use of simulation/stimulation will provide a controlled environment for concept evaluation, however the use of real

machinery, even at reduced scale, will provide an extra level of confidence in system performance. A critical aspect of the system level demonstration is the simulation of the combat system interface. While it is not possible to define this interface exactly at this point in time, it is still important that the generic capability of the machinery system to respond to combat system priorities be demonstrated. In that context, two probable scenarios are of interest:

(1) power demand exceeds available capacity requiring that power redirected to higher priority users (eg. redirection of propulsion power to pulse power combat loads)

(2) loss of part of the machinery system (including part of the MCMS) requiring reconfiguration around damage to maintain power to vital combat systems.

The latter also addresses the Damage Control Management System interface.

The ultimate product of the demonstration phase will be guidance for development of the system and component specifications for procurement of the militarized system. However, continued test and evaluation during the contracting and early design effort will contribute additional information for the militarized system development. Test and evaluation of the system at a Land Based Test Facility (LBTF) would result in finalizing the MCMS specifications for the BFC.

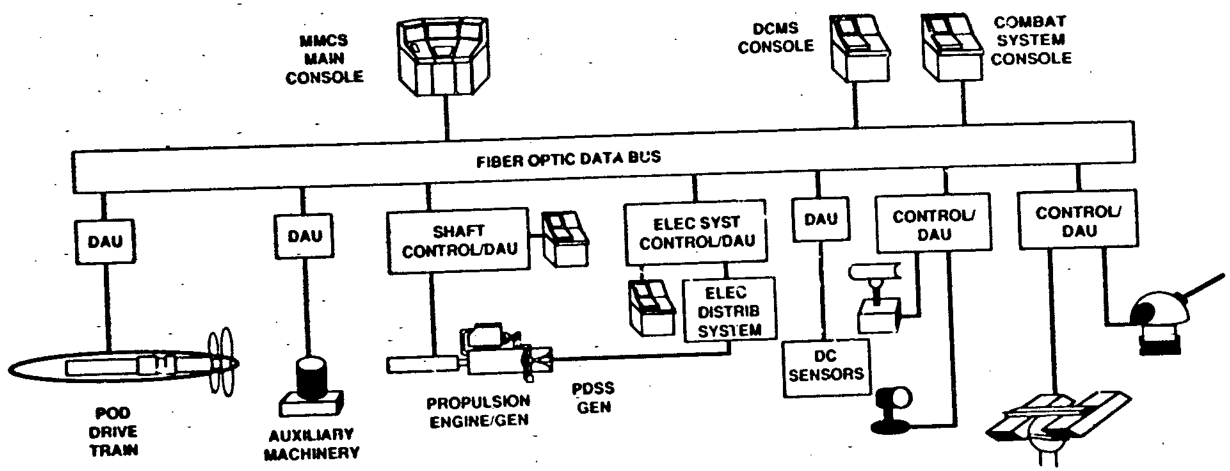
5. SUMMARY

Development of the advanced MCMS will enable the ship characteristics required for the 2010 surface combatant. It will provide the means for integration of the ship combat and control systems with the HM&E machinery systems. The capability to rapidly reconfigure in anticipation of and in response to damage will result in improved survivability and the ability to fight hurt. Real-time condition monitoring of the HM&E equipment with a system that is itself reliable and easily maintained will improve machinery system reliability/availability. In conjunction with embedded operator training and real-time equipment readiness assessment, this will also enhance ship readiness. Reduction or at least control of signatures will result from the capability to monitor machinery vibrations etc. Reductions in the manhours necessary for operation and maintenance of the machinery systems will provide the potential for reduced manning.

The manpower reduction plus any fuel savings accrued due to a well maintained machinery system will reduce overall operational costs. Standardization of hardware and software will reduce MCMS

support costs. The utilization of distributed controls and fiber optics technology will greatly support the goal of improved survivability.

The driving force behind all these advances in Controls Engineering is undoubtedly the breakthroughs in Automation. Harnessing the powers of Automation for the benefit of Controls, is one of the formidable challenges that we are faced with.



WHY DO WE NEED IT?

- TOTAL SHIP INFORMATION MANAGEMENT.
- REDUCED MANNING
- INCREASED OPERABILITY
- INCREASED AVAILABILITY
- INCREASED SURVIVABILITY

FIGURE 1 – MACHINERY MONITORING AND CONTROL SYSTEM – WHAT IS IT?

7.790 32

ADVANCED MONITORING AND CONTROL SYSTEM

PRIORTY A

- o COOPERATIVE ENGAGEMENT
- ● INTEGRATED MACHINERY SYSTEMS
- ● SURVIVABILITY & ABILITY TO FIGHT

PRIORTY B

- ● EMBEDDED READINESS ASSESSMENT, MISSION PLANNING & TRAINING
- ● CONDITION BASED MAINTENANCE
- o TORPEDO DEFENSE

PRIORTY C

- ● COLOCATION OF SHIP CONTROL AND CIC
- o ACCESS CONTROL AND SECURITY
- o ALTERNATIVE USE OF VOLUME

PRIORTY D

- o SMOOTH TOPSIDES
- ● NEW INFORMATION MANAGEMENT
- o ORGANIC AVIATION & OTHER OFF-BOARD VEHICLES

● = DIRECTLY ENABLED BY ADVANCED MONITORING & CONTROL SYSTEM

FIGURE 2 – SOCS IMPERATIVE CHARATERISTICS

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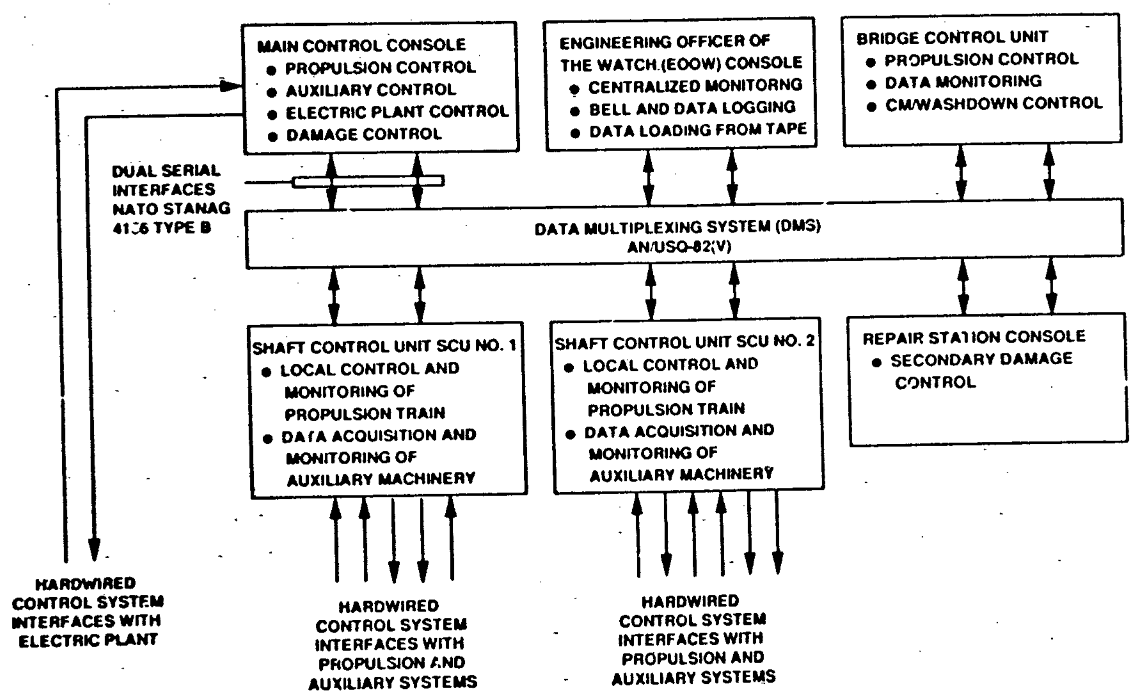

FIGURE 3 – DDG 51 BASIC CONTROL ARCHITECTURE

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ADVANCED MONITORING AND CONTROL SYSTEM

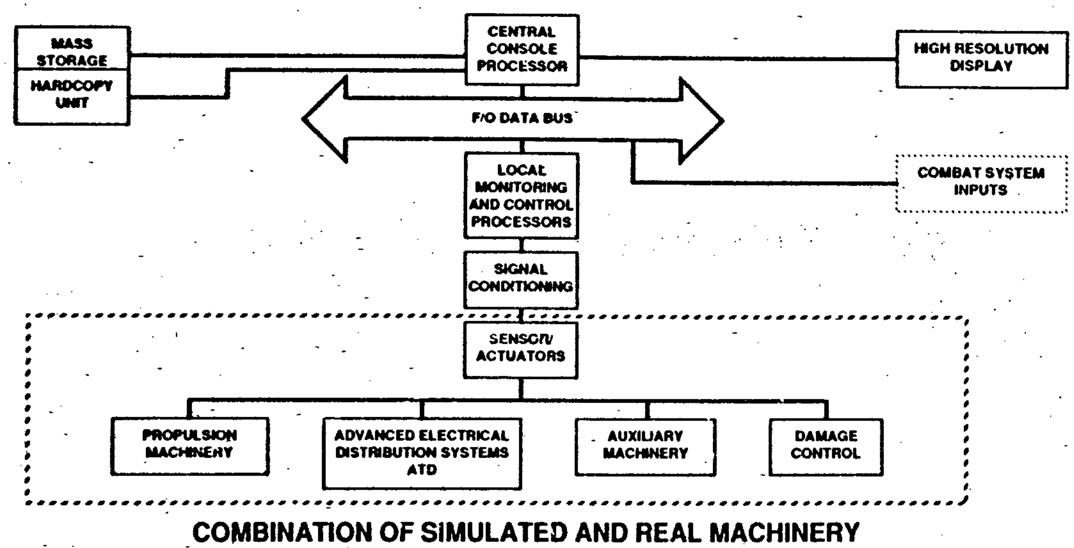

FIGURE 4 – SYSTEM CONFIGURATION

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SHIP CONTROL AUTOMATION AND THE CANADIAN NAVY

by Cdr D.J. Marshall
Department of National Defence, Canada

1. ABSTRACT

In the Canadian Navy, the application of digital technology to total ship control has been dictated by increasingly complex machinery plants, reduced manning targets, and requirements for greater survivability and flexibility. In the merchant marine, the need to achieve real reductions in manning levels and operating costs has led to the widespread application of microprocessors and to the adoption of automatic control processes. In the Navy, at least, reduced manning has been achieved but not necessarily by virtue of these advances. While Navies are reluctant to embrace full automatic (and unmanned) control, integration of the complete marine plant has been achieved. In both environs, the same technology is being adopted to support trend monitoring, machinery health analysis and, in some cases, offboard maintenance management.

The trend is clearly towards increased levels of control, integration, and the application of data processing to the business of keeping our ships at sea. Given the speed with which the technology around us is changing, our achievements to date must be viewed as only one step in a continuum. On this basis, this paper will examine current applications of automation concepts to platform control in Canada, assess their impact on maintenance and training, and discuss the climate for similar advances in the near and long term.

2. INTRODUCTION

For the first half of this century, marine plant and control system designs advanced at a near-equal pace. Machinery plants were large, reasonably complex and, in the case of warships, distributed. Control of the plant relied almost entirely upon a large number of operators, whose task was only gradually eased with wider adoption of centrifugal governors, float-operated valves and similar closed-loop devices. Although local operating positions and improved remote monitoring devices were introduced, the first significant change was driven by ship response considerations, increasing plant complexity, and the need to reduce

operating costs. Remote, but not necessarily automatic, operation of the machinery from a central location forced designers to install larger numbers of sensors and actuators, and to provide a control room from which crew members could operate the plant.

As machinery systems evolved, system response requirements became too great for continuous, manual operation of actuators. Economic pressures to reduce manning levels intensified and the elements of remote control gave way to closed-loop controllers. Hydro-mechanical and hydro-pneumatic components developed for industrial applications were adopted to manage specific operations. A need for periodic re-calibration emerged, but the one-for-one functional modularity of these "conventional" control systems still permitted ready understanding of their operation.

The advent of solid-state devices signalled the end of this parallel growth stage. Remote monitoring, data logging and alarm systems supplemented - and soon became integrated with - control systems exercising autonomous start/stop sequencing and full-authority closed loop control. With the major advances in micro-electronics technology, centralized control systems employing a small number of operators have yielded to more powerful and versatile systems offering increased flexibility, reliability and (at least in the merchant marine) completely unattended engine rooms. These first generation integrated machinery control systems yet to achieve <u>widespread</u> acceptance, yet initiatives to develop shipwide or platform control systems are well underway.

Clearly, advances continue to be made in mechanical and electrical systems; however, growth in the control engineering field is overwhelming. As these rates of change continue to diverge, a very different problem is presented to ship designers and owners - how to balance between the "requirements pull" and the "technology push" in vessels which will almost certainly outlive the control system technology adopted at build.

3. CANADIAN SHIP CONTROL ACTIVITIES

The "state-of-the-art" in Canadian control system designs is embodied in SHINMACS*, the SHipboard INtegrated MAchinery Control System. Its production derivatives are being installed in the Canadian Patrol Frigates and the DDH 280s (in the latter instance as a replacement system under the Tribal Update and Modernization Project). One architecture - that of the CPF IMCS - is pictured in Figure 1. Intelligent Remote Terminal Units located near the controlled machinery acquire and process all plant data, execute all fast-acting closed loop control algorithms, transmit warning,

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* SHINMACS is a trademark of the Department of National Defence, Canada

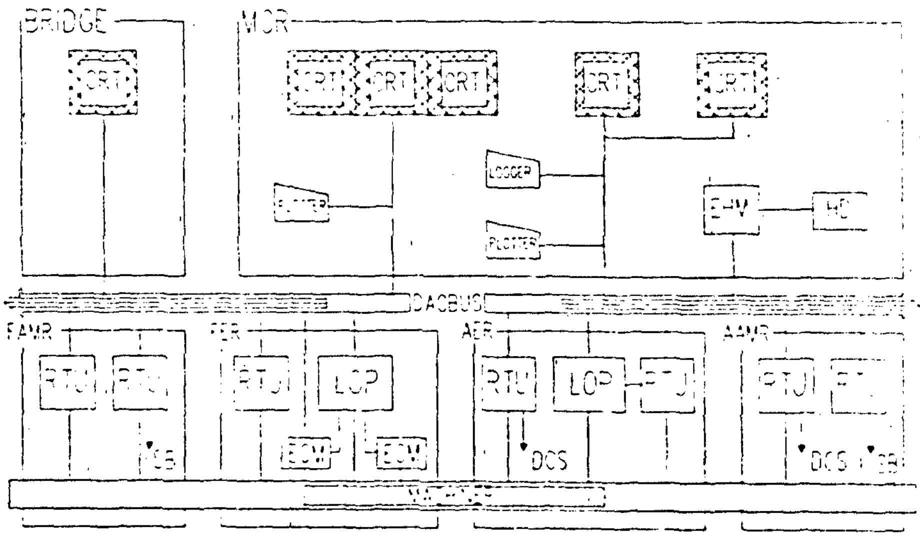

Figure 1. CPF Integrated Machinery Control System

alarm and system fault data to all operator consoles, and effect ordered changes to the plant state. The RTUs contain the RS-422 interfaces to the Damage Control System and the switchboards, and provide full-authority control over the GE LM-2500 gas turbines through Engine Control Modules (ECM) developed for CPF. A versatile Local Operating Panel in each engine room supports full control of the entire machinery plant (via electro-luminescent displays) while providing reversionary manual control. All data is transmitted over a triplicated serial data bus whilst advanced CRT-based consoles in the Machinery Control Room and Bridge provide the operator-machine interface. The reader is referred to (1,2) for a more detailed description of these systems.

3.1 IMCS Status

Over the next decade, sixteen IMCS-fitted ships will enter service in the Canadian Navy - twelve Canadian Patrol Frigates (CPF) and four modernized DDH 280s. At the time of writing, the first-of-class CPF (HMCS Halifax) was well into the alongside trials program; Contractor's Sea Trials were scheduled to begin in late June 1990. The follow-on ships are in various stages of construction (a unit-assembly process has been adopted) with HMCS Vancouver (CPF-02) nearly ready for float-up. TRUMP has been subject to some of the delays inherent in a major conversion, but the first updated DDH-280 will re-enter service later this year.

Though this paper is not intended to discuss the IMCS implementation process in great detail, it is appropriate to summarize some of the high and low points in order to address the impact that introduction of this system will have on the Navy.

3.2 IMCS Achievements

First and foremost, a consistent control system architecture and software structure have been achieved for all new construction. All the intelligent printed circuit boards in each of CPF and TRUMP are physically identical, though the software obviously differs from board to board. Each TRUMP signal processing card is common to CPF. (The reverse is not true as some CPF functions are not implemented in TRUMP). For example, the CPF LM-2500 ECM was tailored to control the P&W FT4A remaining in the DDH 280. In total, there are fewer than 20 different cards in the entire IMCS family.

The operator-machine interfaces are of identical form, near-identical layout and, in terms of the visual page displays and concepts for control and monitoring, highly consistent. As one would expect, the local operating positions reflect the different machinery plants, but the layout and design are uniform. While the Navy is still faced with the challenge of training an established cadre of sailors to operate and maintain a sophisticated IMCS and machinery plant, much of the IMCS training is common.

Perhaps most important, a majority of the software is truly common - 60% of the software developed for CPF was transported to TRUMP without change. The degree of module commonality after integration, certification, set-to-work and trials remains to be seen; however, a single support infrastructure is certain.

3.3 IMCS Shortfalls

Given that the Canadian Navy has not yet accepted the first CPF, the "jury is still out" on the success of the SHINMACS/IMCS development and procurement cycle. Nevertheless, with respect to actual IMCS design, development and testing, some interesting challenges have been - and continue to be - presented. To some extent, these relate to a conflict between the pace of technology and the contracting approach adopted. The reader is referred to (3) for a more thorough analysis of this dichotomy; however, it stems from the assertion that, in general, shipyards lack a comprehensive understanding of integrated machinery control technologies while the associated systems house(s) and vendor(s) do not necessarily appreciate the incredible complexity of warship construction. It is the author's view that the tiered contracting and successive interpretation which inevitably result are largely inconsistent with the technologies considered.

One example of the impact that interpretation can have on what should be a consistent design has to do with system reserve. In CPF, the specified on-delivery reserve of 20% memory and processing power was interpreted to include card-space in each RTU and console. In TRUMP, the same basic specification was viewed quite differently. The result is that all spare card capacity will be in the one RTU well forward in the ship (where it is of no use whatsoever) leaving near-zero growth in the machinery space RTUs.

A second area where the need to interpret specifications can have an undesirable impact concerns sensor selection. Although the CPF "point count" is roughly 2500 (excluding damage control and electrical control sensors and interfaces) a disproportionately high number of discrete (ie, on/off) sensors were selected in response to a performance specification. The result (a proportionately small number of analogue devices and relatively few automatic algorithms outside of propulsion control) will likely lead IMCS operators to react, rather than to watchkeep.

There is no doubt that the physical, performance, and environmental requirements of the IMCS contracts will be satisfied. However, the detailed functional design is where the greatest degree of interpretation has taken place and, consequently, is the area of greatest uncertainty. Given the developmental nature of the IMCS (3), it is argued that too much design responsibility was assigned, leaving naval technical authorities and end-users with too little insight or visibility.

It is unlikely that much can be done to "tighten" specifications in a performance-based procurement. Unquestionably, digital technology permits built-in redundancy, survivability and, above all, a degree of flexibility which would not be practically or economically achieved with hardware components. Unfortunately, tight specifications in support of such design goals are somewhat more difficult to produce. Meanwhile, marine systems designers have not been standing still. The Type 23 CODLAG and the CPF cross-connected CODOG arrangements achieve still higher levels of survivability and flexibility. However, some interesting control problems are usually discovered during the design stage - well after the procurement contract has been awarded. To complicate the issue, Navies all insist on keeping the man in the control loop. Hence, not only have we developed complex propulsion plants, but we have demanded that the plant be controlled from a number of locations in a number of different configurations and that operators remain in control (to varying degrees). While it is most difficult to completely specify control system requirements under these constraints, it is impossible if the marine plant design is not finalized until years after the control specification is passed to the system vendor.

The approach adopted has been to demand (and, by extension, to review) documentation describing the design in ever-increasing detail at each growth stage. By way of illustration, the CPF IMCS System Design document comprises 1800 pages; the Software Design Documents occupy 26 volumes; Factory Acceptance Test procedures add 1200 pages. Our corporate ability to absorb and critically assess such huge quantities of technical documentation is questionable. There is nothing to be gained by even more paper - what we do need is a better way of gaining insight at each stage of the design/development to assure ourselves that the design is actually proceeding as envisioned.

4. IMPACT ON MAINTENANCE AND TRAINING

With the increased emphasis on software and reduced complements, IMCS will rely more heavily than control systems of the past on support from private industry. Such support will have to reside in each Dockyard and at the third level system support facility. Likewise, the technicians who are tasked to maintain those systems are faced with a challenge very much greater than in the past.

4.1 Maintenance

Clearly, systems such as IMCS are supported by extensive on-line BITE and off-line diagnostics as standard features, consistent with repair-by-replacement or maintenance-by-exchange philosophies. That BITE will not detect <u>all</u> hardware faults is widely accepted for economical reasons; but what of the software? Controlled change (driven by a change in the machinery plant or by some necessary change in the application software) can be managed in a fairly straight-forward manner but the potential for a serious software fault at sea must be considered. Given that few Navies can afford to have software engineers at sea, how do we diagnose and rectify software faults whilst underway? Assuming that the problem can be described in sufficient functional and technical detail to permit duplication and identification in a system support facility ashore, do we even attempt to effect a fix? Or do we rely on the reversionary modes to get us home?

These are but a few of the key considerations which must be addressed in setting and implementing the maintenance philosophy for such control systems. A comprehensive system (software) support facility is critical. In Canada, Departmental policy prohibits in-house support of systems which do not use DND-standard computers (the AN/UYK family) and languages (Ada, CMS-2M). As a consequence, the IMCS system support facility will be established in - and operated by - private industry. In actual fact, the rate of change in IMCS configurations after the first few years in service <u>should</u> be relatively low, thereby negating an argument for expansion of the in-house infrastructure.

Nevertheless, the configuration will vary between ships - if only during the period (years?) in which a software revision is being implemented. Hence, marine systems engineers in Canada are being thrust into the arenas of configuration management and integrated logistics support arena to a greater extent than ever before. Whilst IMCS is but one of the systems requiring close attention to detail, "simple" IMCS support questions have a profound impact. For example, the ROM-based IMCS must be supported by a set of spare, pre-programmed cards. Given that the single system support facility is located thousands of miles away, the next question becomes, "where does one burn the PROMs?"

Onboard PROM-burning has thus far been rejected as a normal course of action for the same reason that on-board patching is prohibited - configuration control cannot be assured. However, serial-number control of a very large number of individual cards is implied if the boards are burned only at the support facility. The compromise adopted will be to burn the cards in the Dockyard, thereby reducing the number of line items held in inventory, yet assuring the Fleet of responsive support. For such a maintenance concept to succeed, the configuration management system must be faultless.

4.2 Training

CPF and TRUMP IMCS operator training will be supported by comprehensive shore-based, real-time training facilities comprising a Computer-Based Training System for part-task and procedural training, and full IMCS trainers for actual control system training. Indeed, the provision of such trainers tends to acknowledge for the first time that the engineering watch team has a team training requirement not dissimilar to that of a combat operations team. Recognizing both the flexibility of the IMCS architecture (2) and the desire to minimize training time ashore, an onboard trainer is being examined outside of the CPF and TRUMP contracts. An Advanced Development Model is expected to be completed in 1991.

With respect to maintenance training, it is often argued that systems such as the IMCS can be supported entirely through repair-by-replacement schemes and that a highly-trained technical staff is not therefore required. Certainly, such arguments are supported by the promising reliability and availability figures "predicted" at contract award. However, we have concluded that ship control system maintenance entails a great deal more than replacement of defective components. While the control technicians will undoubtedly be faced with a significant sensor maintenance load, it is anticipated that their most difficult problems will involve system interfaces, and not necessarily limited to the hardware interface components.

Lengthy analyses over the past twelve years concluded that the maintenance requirements of the soon-to-be-acquired IMCS (and the emergency analysis and repair requirements in particular) could not be undertaken by any existing naval occupation. The training delta was considered to be too great for inclusion in either a specialty training course for selected technicians or as part of core or career training for a selected occupation. As a consequence, a new technical occupation is being created within the marine engineering branch. The Control and Instrument Technician will be responsible for all onboard control system maintenance. Although only three or four of these technologist-level trained maintainers will be established in each ship, they will be responsible for conducting all system diagnostics and repair, sensor calibration and replacement, and - under very specific and controlled circumstances - software repair. The first class of these technicians will enter a community college training program in September 1990 and be available to fulfill their maintenance responsibilities in 1993.

5. THE CLIMATE FOR IMCS ADVANCEMENT

Over the next decade, the greatest attention will be paid to the in-service aspects of IMCS. The tasks of accepting sixteen complex systems into service over a relatively short period of time <u>and</u> establishing a comprehensive support arrangement in the private sector are significant.

This need to focus on <u>in-service</u> support comes at a time of increased pressure on all defence expenditures. Most western countries are being forced to address their national debts and deficits with tight fiscal and monetary policies coincident with a diminishing threat. Although a "peace dividend" may or may not be realized, all aspects of defence budgets (capital, operations and maintenance, personnel) are being critically examined. In Canada, capital expenditures apart from CPF, TRUMP and the Naval Reserve Modernization Project are uncertain. It is appropriate, therefore, that we concentrate on establishing the baseline on which to support and expand the IMCS systems.

Considerable emphasis will be placed on the state of IMCS software. The SHINMACS Advanced Development Model was developed under a set of [in-house] Naval Software Standards. In the meantime, DOD-STD-1679 has come and been superceded by DOD-STD-2167/2168. The software industry has begun to exhibit somewhat more discipline in developing application software, and structured tools (CAE/CASE) are being adopted to good effect. Although no wholesale re-design of the IMCS software is at all contemplated, these tools and structures will be applied wherever possible to the IMCS support activity.

Given the expected down-turn in capital expenditure, our attention will again shift to promising areas of R&D, with somewhat greater emphasis on developments having the greatest potential "bang-for-the-buck".

The SHINMACS design was always cognizant of the potential for shipwide monitoring for maintenance purposes and, consistent with our shift to condition-based maintenance, the capabilities of the IMCS will be exploited. We plan to implement a number of already-developed condition monitoring and assessment packages but will likely not incorporate any expert/knowledge-based system until the investment is clearly justified.

Although the trend to platform control is clear and obvious, there appear to be few targets on the Canadian horizon. We are unlikely to occupy ourselves with the challenge of complete platform integration much before CPF mid-life or DDH 280 replacement. As a consequence, the application of such ship-wide technologies as optical fiber buses, and full-scale integration of voice, video and data will probably not be pursued beyond the Advanced Development stage (unless, of course, significant EMI problems force us in that direction).

Given the virtual certainty that the very large number of sensors result in a higher-than-anticipated maintenance load, we will continue to search for, and if necessary develop, reliable, accurate sensors. In this regard, optical fiber-based sensors offer considerable promise, though their application at present appears limited to high value components. We will continue to concentrate on improving the operator-machine interface, thereby maintaining our expertise in that field. The demonstration of an IMCS onboard trainer will likely be the first product of that activity.

6. CONCLUSION

This paper has described the state of ship and machinery control system acquisition in Canada. By and large, the technology embraced in the Integrated Machinery Control Systems being fitted in our Patrol Frigates and DDH 280 Class destroyers has had - or will have - a major impact on every aspect of the system life cycle and the manner in which we do business. To maintain the operational availability of our ships, private industry is being solicited to provide the necessary support for a critical shipboard system - a new endeavour for both Canadian industry and the Navy.

The demand to reduce crew sizes has resulted in requirements for greater automation and integration. Although these requirements have not been wholly satisfied, shipboard complements have been reduced nonetheless. At the same time, the conflict between

newly-adopted maintenance philosophies and the level of sophistication of the control system will have a profound effect on the manner in which we train our men, and may well be the greatest challenge facing us.

Finally, advances in technology will continue to "push" us in unexpected directions. We must maintain our ability to recognize, examine and innovatively implement the most promising of those developments if we are to maintain our operational effectiveness as a Navy.

7. DISCLAIMER

The opinions expressed herein are those of the author and do not necessarily reflect the views of the Department of National Defence, Canada.

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A REVIEW OF THE PAST 3 YEARS ACHIEVEMENTS AND FUTURE AIMS IN MACHINERY CONTROL AND SURVEILLANCE FOR THE ROYAL NAVY

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1. ABSTRACT

This paper aims to review the achievements in Machinery Control and Surveillance systems from the RN point of view, recording the successes and lessons learned in both analogue and digitial systems. This will cover both new design ships and retrofitting to existing classes of ships.

Having procured these latest software controlled digital systems, consideration has been given to the configuration control and support of the system in service and this aspect will be addressed together with the possibility of using the latest Information Technology for economy of effort and improved efficiency. Additionally the needs and benefits of shore based assessment of machinery control and surveillance systems and the need of training equipments and organisations are discussed to ensure that the advances in electronic systems are matched by the adequate operation and maintenance training to obtain maximum benefit to the service.

Future evolutionary changes to Machinery Control and Surveillance systems to take advantage of further advances in networking and producing an Integrated Platform Management System will be considered together with the opportunities of implementation into the fleet.

2. INTRODUCTION

At the two previous symposia ref (1)(2) I have given a brief review of the progress along the technological pathway which has taken the controls and surveillance technology from the analogue electronics applications of the 1970's to the exploratory applications of digital systems on shore and then the decision in 1982 to go to a more embracing digital system for the Type 23 Frigate and later the single role minehunter.

This trend is continuing and all new design ships will utilise digital technology to a greater extent than the previous examples, however caution in the world of controls for ships is

such that we have not yet reached the "fly by Wire" philosophy of the aircraft world.

Nevertheless digital technology is here and will occupy centre stage for some years to come as its advantages and disadvantages are completely understood by its practitioners and its applications permiate the control and surveillance needs of the whole ship.

Integrated Platform Management Systems are now beginning to be applied at the outset to new ship designs to capitalise upon the system ability to manage, control and survey the whole of the platform facilities with reduced manpower yet increased efficiency.They will in turn require the consideration of human factors involved in such a management strategy. Cognitive overload could be relieved by the judicious application of Expert Systems assistance which used the man to his maximum ability without reaching his capability limit.

3. ACHIEVEMENTS

So much for the background, now I would like to consider the achievements.

Within the last 3 years, the batch 3 of the Type 22 Frigates has been completed and totally accepted into the Royal Navy. This batch of ships was the last to use analogue technology for the Machinery Control and Surveillance System, being procured before digital systems had reached sufficient confidence in development. It can be recorded that the system provided by HSDE has passed all its tests and trials with flying colours and does not figure in reports of design shortcomings from sea.

Turning now to the Type 23 Frigate, HMS NORFOLK is the first of class built by Yarrow Shipbuilders Ltd and as I write has completed many trials of her programme. From my point of view the Machinery Control and Surveillance System based on the Vosper Thornycroft Controls D86 has performed very satisfactorily with few errors of design being exposed during the programme.

This satisfactory state of affairs can in part be attributed to the shore test and assessment undertaken by the Admiralty Engineering Laboratory at West Drayton on behalf of the Sea Systems Controllerate. This assessment programme is the subject of another paper at this Symposium by Mr Keith Chilvers and therefore I will not go into detail here, however I must record the fact that such shore assessment is essential for this and future Machinery Control and Surveillance Systems as their complexity and essentiality to ship performance increase to at least equal a Weapons System. Shore based test and evaluations

combined with a permanent reference set has been the norm for Weapon Systems and it is essential that reference sets must be established for Machinery Control and Surveillance Systems for these new classes of ship. This requirement is being written into the Staff Requirements for new designs, I trust its essentiality is recognised for sound ship procurement and support. The MCAS system is set to grow into Integrated Platform Management System and even more than the present designs it will form the bond between the innumerable individual items of equipment which make up the whole platform system.

The second class of ship now being proven is the Single Role Minehunter built by Vosper Thornycroft (UK) the first of class being HMS SANDOWN. Again I am pleased to report that the Machinery Control and Surveillance System based on the VTC D86 has performed extremely well.

Briefly the Machinery Control and Surveillance System can be controlled from the Quartermasters console on the bridge, extensions on the bridge wings, from the quarter deck and from the AIO.

'he outstanding ability to hover, change direction and crash stops is attributable to the Voith Schneider propulsors under the control and surveillance of this installed system.

Once again this control console and associated digital electronics was given an exhaustive on-shore assessment at Cambridge Consultants Ltd. This task and results are the subject of a paper at this Symposium by Mr Steve Jeanes of Cambridge Consultants Ltd and Mr R E Bishop, MOD UK.

Two other applications of the VTC D86 digital system nearing completion of trials are those for the surveillance systems in HMS VANGUARD and Type 2400 Submarine HMS UPHOLDER. I mention these now as although not for discussion at this Symposium they figure in the support activity being set up for the Surface Ships D86 systems.

This support activity is itself worthy of mention as its aim is to provide common configuration control of the many hundred electrical boards which will be in-service in due course. Information Technology attributes will be used to the full in order to minimise manpower but achieve maximum control over modifications of hardware and software and instant access to each particular ship fit record.

Continuing on the theme of achievements and hopefully it is approaching the status of achieved, is the design and provision of the comprehensive Machinery Control and Surveillance System

for the Auxiliary Oiler and Replenishment Ship the first of which is on Fort Victoria.

This system is based upon the HSDE D6000 system and incorporates the surveillance of 4000 points including the cargo and ballast systems.

The system configuration has distributed control and surveillance by location to minimise cabling between plant and outstations with the outstations located to share evenly as far as possible the signal inputs and outputs. For critical services back up is provided by dedicated direct circuits.

A feature of the system is the multiple control positions provided for example Bridge, MCR, Damage Control HQ etc. A fuller description of the system has been published in the proceedings of the Institute of Marine Engineers on 5 December 1989 in a paper by Mr C T Marwood.

The above applications of digital systems have been to new design ships, however the first of an existing 18 year old coastal survey vessels HMS BULLDOG has just completed its acceptance trials of an HSDE designed and supplied control system based on their D5000 8 bit system.

This new Propulsion Control System is designed to coordinate the propulsion machinery to provide the desired ship performance while preventing unsafe operation and without exceeding the machinery stress limitations. To achieve this aim the system provides automatic control of the 2 shafts with their associated diesel engines and controllable pitch propellers. The automatic control functions include the clutches and shaft brakes in addition to providing scheduled control of engines and propeller pitch. The system provides an approximately linear relationship between power control lever position and ships speed. Fully automatic control is available from the MCR and bridge with extensions to the bridge wings.

The system provides automatic load sharing between the 2 engines on each shaft and additional facilities for monitoring of machinery status, warning of abnormal conditions combined with a diagnostic capability via the maintainers system monitoring panel.

I have quoted this example to illustrate the incorporation of new technology into an older ship is both feasible and has improved performance in particular for this ship class in the Man Machine Interface and the propulsion power balance.

4. TRAINING

As I stated at the 8th Symposium the introduction of digital control systems into the Royal Navy was a major technological step forward offering control systems which should be more powerful, flexible and reliable and easier to operate, maintain and support.

We have now reached the point in time at which digital Control and Surveillance Systems are accepted into ships at sea and the degree of success of the system is now being put to the test in that the ability of the ships crew to operate and maintain the system has high visibility.

The T23 Operator and Maintainer Trainer was successfully commissioned in January 1989 and has been in regular use since that date both to train ships personnel and others involved in setting to work the follow on ships.

In addition to the full Machinery Control and Surveillance Panel the T23 Trainer incorporates emulated local control panels for the major propulsion and electrical equipments. Furthermore the auxilary systems can be operated via interactive VDUs thus allowing full recovery action to be taken for all major machinery breakdown exercises.

The single role minehunter operator and maintainer trainer is in the course of procurement, the contract was let on Rediffusion Ltd in September 1989 with a completion date of April 1991.

This trainer will offer a fully integrated training environment within a single classroom. The full scale machinery control console and switchboard drive a complete computer simulation of the machinery and electrical equipment. Three work stations can be configured to act as interactive local control panels for the Voith Schneider Propulsors, bow thrusters and main engines. These work stations can also provide computer based training for all main and auxiliary machinery and systems and maintenance such as fault finding training for the D86 equipment on board the SRMH.

In support of both of these trainers is the installation of D86 elements on which the Navy maintainers obtain their basic understanding of the units which they will meet in the many controls and surveillance systems installed in the Royal Navy.

5. SUPPLEMENTARY SYSTEMS

The life span of ships and electronic devices is markedly different and existing ship classes are often using technology 15 years old. Such installations can be adequate however often a marked improvement in plant management can be achieved by replacing existing Control and Surveillance equipment by todays model.

Many examples can spring to mind however I will mention 2 examples which are in the process of being implemented into the RN.

The first is the Teddington Mark 6 local control and surveillance panel which uses digital technology and is markedly smaller than the analogue item it replaces which is now becoming unsupportable. It is used for the control and surveillance of diesel generators, compressors, cold rooms etc.

The second item is the Decca Isis 250 series which is progressively replacing the Type 300 as it becomes unmaintainable. The 250 uses digital technology and colour VDUs to provide an extensive surveillance system with a control option if desired. Messrs Pymm and Paddock will present a paper on the 250 at this Symposium and will obviously cover the system in detail.

A running programme of installation "where needed" is in hand balancing the technological need against the cost of these items.

6. FUTURE AIMS AND APPLICATIONS

Digital technology in ships now entering service has essentially been cautious, engendered by the very nature of the role required and the proof of reliability of this new, to the Navy, technology.

The surveillance mode has advanced with more speed and the benefits of remote and comprehensive surveillance have been welcomed together with the reduction in manning which has been brought about.

Most effort in ship control systems designed in recent years has been expended on the consideration of interactive sub systems such as propulsion, steering, stabilisation, electrical power generation as though they were independent entities. There is now active consideration being given to the integration of these individual systems into Integrated Platform Management System.

The generations of ships now being designed will address this philosophy with the intent of introducing IPMS with the aim of improving the management of the total platform facilities and reducing or making more effective the manning of the platform.

Such a system will access a very large quantity of surveillance information and this in turn will require management changes. One possible solution is the use of an Expert System or Intelligent Knowledge Based System to process the incoming surveillance information and to prioritise the alarms and warnings such that the watchkeeper is not overwhelmed by the flood of information which could occur under fault or action damage condition.

The rapid increase in the size of control and surveillance systems, particularly the latter, is identifying the limitations of the serial Von Neumann architectural approach. I believe that parallel processing using transputers combined with the traditional approach will be necessary to cope successfully with the increased demands associated with IPMS or any IKBS support designed into future ship systems.

A particular area of surveillance which may benefit from the application of digital technology is that of damage control and surveillance as developments in this area have generally lagged behind those in machinery control. For example, fire alarms appear on one panel with flood alarms appearing elsewhere, similarly other information is held on a variety of stateboards and in books. A much more effective presentation of information is needed. The latest damage surveillance system to enter service is that of the Type 23 Frigates where fire, flood, and door and hatch status all appear on one alarm panel similar equipments are being produced for our latest submarines.

A new system has also been developed for the Type 23 Frigate to provide an efficient presentation of other items of important data. Further developments using smart sensors distributed processing and expert systems are also being investigated against the background of reduced manning. A paper will be presented at this Symposium by Mr Richard Bryant which will discuss the developments.

7. CONCLUSIONS

During the last 3 years considerable effort by industry and MOD has brought the paper designs of digital control and surveillance into reality. Ships are now at sea using the early 1980 designs in the real environment and registering considerable success in reducing manning and improving power management. However there is considerable stretch potential yet to be

exploited and present and future specifications and resulting designs should capitalise upon the efficient management of the total platform.

Platform system engineering must be acknowledged as an essential ingredient in the design of future warships and digital technology is one tool in the achievement of this aim.

Disclaimer. The views expressed in this paper are those of the author and not necessarily those of the MOD(UK).

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TYPE 22 FRIGATES BATCH 3

'ANALOGUE' MCAS

HMS SHEFFIFLD
HMS COVENTRY
HMS CORNWALL
HMS CUMBERLAND
HMS CAMPBELTOWN
HMS CHATHAM

MCAS DIGITAL PROGRESS

1978 – DEMONSTRATION ON SHORE
1982 – TYPE 23 FRIGATE
1984 – SRMH
1984 – A.O.R
1990 – FUTURE FRIGATE

TYPE 23 FRIGATES

DIGITAL MCAS

HMS NORFOLK	–	ON TRIALS
HMS MARLBOROUGH	–	ON TRIALS
HMS ARGYLL	–	BUILDING
HMS LANCASTER	–	BUILDING
HMS IRON DUKE	–	BUILDING
HMS MONMOUTH	–	BUILDING
HMS MONTROSE	–	BUILDING

AUXILIARY OILER REPLENISHMENT SHIP

FORT VICTORIA – LAUNCHED
FORT GEORGE – BUILDING

CONCLUSIONS

DIGITAL SYSTEMS ARE HERE!

MMI DESIGN IS IMPROVED

IPMS IS THE NEXT LOGICAL STEP

EXPERT SYSTEMS MAY HAVE
A PART TO PLAY

THE LATEST DEVELOPMENTS REGARDING PLATFORM AUTOMATION IN THE NETHERLANDS

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1. SUMMARY

The Multipurpose or M-frigate of the Royal Netherlands Navy and the role of the Integrated Control and Monitoring System (ICMS) of its platform are briefly introduced.
The factors which have played major roles in the design of the ICMS are discussed:
- improvement of the fleet's output to cost ratio;
- experience with S-frigates of the Kortenaer-class;
- experience with the ICMS of Walrus-class submarines.

The concept of the ICMS is explained, its design program touched and a conclusion provided.

The latest developments regarding the ship control systems in the Merchant Navy will be discussed.

2. INTRODUCTION

During the 8th Ship Control Systems Symposium at The Hague, 1987, the platform automation of the M-frigates under construction at Royal Schelde Shipyard has been broadly reviewed (1).
Eight of these M-frigates are under construction for the Royal Netherlands Navy.
The first of class, to be commissioned in 1991, has been named Karel Doorman after Rear Admiral Karel Doorman, who was in command of the American/British/Dutch/Australian Combined Striking Force during the Battle in the Java Sea in 1942.
Design took place at the Directorate of Materiel, Royal Netherlands Navy, in close cooperation with:
Royal Schelde Shipyard, NEVESBU (B.V. Nederlandse Verenigde Scheepsbouw Bureaus) as consultants, HSA (Hollandse Signaal Aparaten N.V.) as payload manufacturer and R & H (Van Rietschoten & Houwens) as manufacturer of the electrical installations as well as the ICMS. The platform of the M-frigate comprises a 122 metres long, 3300 tonnes displacement ship, twin shaft, with Lips controllable pitch propellors. Two Rolls Royce Spey SMIA gasturbine units give her up to 29 knots, and two Stork Werkspoor Diesel engines provide her with an action-radius of 6000 nautical miles.
Four 650 kilowatt diesel generator sets and two chilled water plants accommodate her payload and her crew of 154.

Add to this a rudder-roll stabilisation system and a number of NBCD-systems spread over the six Damage Control zones in the ship, and you have an idea of the concept of the platform installations of the M-frigate.
To put the ICMS in its right perception, a brief run through the factors which have led to the concept of the ICMS is necessary. These factors have to be considered when answering the question: are we on the right track with this system?

In the shipping industry quite remarkable changes are still taking place. These changes are almost all related to information technology (IT).
Electronics has brought unforseen possibilities to control systems and communications. The merchant shipping industry, until recently known as a "trend-follower", has now accepted the challenge to apply new technologies right from the start of the design process. These efforts to enlarge application of IT are reflected in extensive research programs in Japan, the USA and Europe, in which the shipping industry is now also involved.
In the meantime an important factor is more and more dominating future operation and design of ships: the environmental requirements.

3. NAVY

Factors leading to the concept of the ICMS

The factors which have led to the concept of the M-frigate ICMS can be placed in the following three groups:
- Fleet output to cost ratio;
- S-frigate experience, and
- Walrus-class submarine ICMS developments.

Fleet output to cost ratio

The first group comprised philosophies of the Royal Netherlands Navy which have as goal "to improve the output to cost ratio of the fleet".
- Stop operator errors.
  Particularly valid for installations onboard naval vessels, which are used by an ever moving chain of operators, and where some systems, because of their nature and purpose, are sporadically used. Especially under battle or damage stress conditions operator failure will become very likely.
  Therefore the Royal Netherlands Navy aims at commonality of man-machine-interfacing (MMI), applies automatic control systems for routine procedures on platform systems, and puts a high emphasis on human factor aspects in MMI design.
- Standardized components and fault diagnosis procedures are seen as ways to curb the cost of training and logistic support.
- Improved reliability of platform systems resulting from a certain degree of automatic control, might give the possibility to limit the specialisation level of operators under

abnormal conditions.
- And finally, all these technical improvements should result in a reduced number of crew members. The cost of personnel is by far the greatest in the annual operating and support costs of a frigate, and will only rise with the decline of Europe's young population.

These factors have greatly influenced the design of the ICMS of the M-frigate, together with, of course, experience with platform control systems already in service in the Royal Netherlands Navy.

S-frigate experience

Experience with watchkeeping and maintenance routines onboard the Standard- or S-frigates of the Kortenaer-class.

Built between 1975 and 1984, these frigates feature:
- double shaft COGOG propulsion;
- unmanned machinery spaces;
- control and monitoring of platform systems, including NBCD-management, centralised in a Ship Control Centre (SCC);
- automated control of propulsion systems;
- direct remote propulsion control from the navigation bridge or from the Combat Information Centre;
- an automatic pilot steering system;
- a fully automatic 4 diesel generator power plant;
- more than 3600 tonnes displacement;
- a crew of 172, of which 40 in the marine engineering department.

As the Ship Control Centre is the nerve centre for platforms systems control, let's concentrate on the SCC of the S-frigate for a moment.
Panel design is such that almost all information is presented simultaneously.
Alarm- and warning annunciators and indicator lamps have been applied, grouped systemwise through coloured frames, adhering to the all-dark principle.
The number of analogue instruments has been kept at a minimum.

The control panel in the S-frigate SCC is divided in the following main sections: electrical power, auxiliaries, propulsion and NBCD.
The maximum number of watchkeepers in the SCC during a routine watch at sea is five (two petty officers and three ratings).

Proven reliability of the platform systems, due to indeed a high level of automation in electrical power distribution and propulsion systems, and a high quality of MMI design in the S-frigate SCC; of course with the technology available at that time, allows a minimum of two watchkeepers to remain in the SCC during routine seawatches.

So, on the S-frigate three members of each standing routine SCC seawatch are available to carry out maintenance jobs at platform systems, day and night.

The Royal Netherlands Navy intends to continu S-frigate watchkeeping- and maintenance routines on the M-frigates, and it was recognised that a reduction in the minimum number of watchkeepers actually present in the SCC at seawatch from 2 to 1 had to be feasible. Under alert state (readiness state 2) a reduction from 8 to 6 watchkeepers would be feasible.
Compared to a S-frigate crew a reduction of 4 marine-engineers has been achieved.

To achieve this crew reduction on board the M-frigate, concentration of all control and monitoring facilities to one operator position had to be realised in the SCC; by implementation of new MMI-concepts.

Walrus-class submarine ICMS developments

Starting from October 1989, the first of the four Walrus-class submarines has carried out its sea-trials.

The Walrus has an unmanned machineryroom and the ICMS contains a number of automated control systems catering for propulsion, for charging and monitoring of the batteries, for diesel plant control and for trimming and ballasting.

The Walrus ICMS, manufactured by Van Rietschoten & Houwens, provides a concentration of controls and monitoring around two operator positions in the command and control centre, and the introduction in the Royal Netherlands Navy of Visual Display Units (VDU) with mimics for monitoring and manipulating platform components (Figure 1). Mimics are schematic pictures, presenting the actual status of platform systems and components.

The Walrus philosophy and the specifications used in its design and application, have been largely applied in the design of the M-frigate ICMS.
No wonder that the Walrus ICMS sea-trials have been eagerly monitored by the M-frigate designers.
It can be said now, that because of the application of the ICMS, the reliability and controllability of conventional submarines have improved greatly.

In harbour, Walrus-class platform control watchkeeping duties are performed, quite satisfactorily, by teams containing crewmembers not belonging to the marine engineering department, including cooks. This routine has shown that the use of mimics on Visual Display Units as man-machine-interface of the ICMS can be very efficient and extremely userfriendly provided the Human Factors aspect of the design is well thought out.
And finally, the ICMS has enabled the Walrus-class submarine to be operated with a more than 25 percent reduction of the number of engineers compared to its predecessor. (with manned machinery spaces).

The M-class frigates

This class of frigates will roughly be featuring:
- double shaft CODOG propulsion;
- unmanned machineryroom;
- Ship Control Centre with Integrated Control and Monitoring System including NBCD-facilities;
- computerised propulsion control, power generation control;
- computerised rudder-roll stabilization;
- 3400 tons;
- crew of 154 (36 marine-engineers).

The concept of the ICMS for the M-frigate

The M-frigate Integrated Control and Monitoring System configuration can be split into four parts. (Figure 2)

The first part is formed by the System Periphery, located in the immediate vicinity of the platform installation it serves. The System Periphery provides independent protection, locking, selection between local or remote control and between manual or automatic control, as well as independent status display of platform installation components. (for instance valves and motors)
For electric controllable components, this is the bottom of the control and monitoring hierarchy.

The second part of the ICMS comprises remote monitoring and manual emergency control from the Ship Control Centre of certain vital platform installation components.

The third part of the ICMS consists of Automatic Control Modules (ACM's).
ACM's are dedicated to closed loop control of a particular platform installation and are located closely to the installations they serve.
Local functional control of a platform installation through its Automatic Control Module is achieved by a dedicated control panel fitted to the casing of the ACM.
ACM's are autonomously operating and redundant powered by AC and DC shipboard systems.
Remote control of a platform installation through its ACM will be realised in two different ways:
- through ACM dedicated remote control panels. The panels can be located on the navigation bridge, on the bridge wings, and/or in the SCC;
- through General Purpose Working Stations in the SCC, which are part of the, so called, Data Processing System.

The Data Processing System (DPS) embodies part four of the ICMS, and its purpose is to provide an adequate and selective means of communication between the operator in

the SCC and the platform components.

These platform components consist of (descending in control and monitoring hierarchy):
- Automatic Control Modules;
- System Periphery, and
- Transducers.

The DPS also handles the data exchange between platform and payload for instance by sending platform information to the selfnoise analysing system.

The Data Processing System is a federated system with eight local front-end processors, positioned throughout the ship close to the platform installations and connected to the control room by redundant fibre-optic links.
Over 1600 platform installation components and their independent periphery, are controlled and monitored by 23 independent ACM's as well as by 1, 2 or 3 operators on General Purpose Working Stations, connected to two redundant Local Area Networks and Central Processors.
The number of platform installation components controlled from the SCC on the M-frigate is twice that on the S-frigate.
Apart from control and monitoring functions, the DPS delivers management functions, such as:
- general status monitoring;
- sensor- and alarmparameter changing;
- signal trend recording;
- datalogging, including running hours and bridge orders;
- ship stability prognosis;
- damage control situation plots, using interactive operator plotting techniques.

The three General Purpose Working Stations, each containing three VDU screens for alarm presentation control and monitoring of a dedicated but selectable set of platform systems. (Figure 3).

Management functions are available on two Management Stations, each with one VDU and one slave monitor in the Combat Information Centre. Two more dedicated operator stations are placed in the damage control centres.

During routine conditions or during transition to higher states of readiness, control and monitoring from the SCC require not more than one operator, i.e. the chief of the watch. During non-routine conditions all three General Purpose Working Stations in the SCC are manned. The additional Management Stations provide a fast and accurate exchange of information between damage-control parties in the ship, the NBCD-management in the SCC and the ship's command in the Combat Information Centre.

The project

Between 1985 and 1990 the Navy design team has spent some 30 man-years on the functional design of the ICMS for the M-frigate.

This design team has laid emphasis on two activities: the production of Functional Specifications and the design of the Man-Machine-Interfacing.

The quality of the products of these two activities determines size and quality of the software of the ICMS.
Time and effort required for the choice and implementation of the right software design technique should not be underestimated.

The Institute for Perception/TNO in the Netherlands is very much involved in the human factors aspect of the MMI-design for the payload as well as for the platform ICMS.
Full size mock-ups of the M-frigate's navigation bridge, the Combat Information Centre and the Ship Control Centre have been built in Soesterberg to support the design-proces.
The Institute for Perception is also involved in the evaluation of the R&H design of the mimics to be used for the colour VDU of the ICMS.
This as a combined effort with the design teams of the Platform Operators Handbooks, and representatives of the Naval Engineering School and the NBC & Damage control School of the Royal Netherlands Navy.

During the past five years it became very evident that only close co-operation between naval constructors, marine engineers, electrical engineers and automation specialists would result in a really integrated and effective control and monitoring system.

In the second half of 1990 first versions of the control modules of the ICMS combined with an interim control and monitoring system are scheduled to go to sea in the first of class of the M-frigates; six years after the start of the contract.
It is expected that eight years after the start of the contract the complete ICMS will be at sea.

4. MERCHANT NAVY

Operations Centre

Parallel with international research regarding implementation and utilisation of advanced IT-systems on board merchant ships, research in the Netherlands has been carried out.
This research is more and more concentrated around activities to evaluate the bridge into a highly integrated Operations Centre (OC).
The target is clear: to operate the ship with one man on the bridge under all conditions and in all waters.
In the Netherlands we have focussed ship control research efforts on the following

subjects:

- Maintenance
  An expert maintenance system will be developped to minimise maintenance costs and to maximise engine availability.
- Weather routing
  To optimise voyage planning, an expert weather routing system will be implemented.
- Electronic chart
  An Electronic Chart Display System is under development. A pilot system will be tested extensively this year on board a ship sailing in the North Sea area.
- Human Factors
  Further research into the determining of stress and high mental workload of the watch officer will be carried out.
  This includes also safety at sea requirements.

Shipping industry is now recovering from a 15 years economic depression.
During the last period of this recession many activities regarding research of innovative ship designs, including automation, were still carried out in several maritime countries.
Evaluation of the results with these innovative ship designs is very valuable for our research today.

It is of interest to summarise these results:

* Cost-benefits calculations proved that investments in high technology is profitable.
* The systems were too complicated and had too many measuring points.
* The bridge was flooded with too much data and information.
* The reliability of the sensors is unsatisfactory expecially those embedded in machines.
* After the initial time of operation with its failures, the automation system is working satisfactorily.
* Crew reduction should be realised with great caution; the technology is available, but we are dealing with human factors, safety and necessary investment costs.

Looking into these results in more detail, we can conclude that future technology on board ships has to be as simple as possible, highly reliable and easy to maintain. The trend that quantity of data generated on board will increase is an inevitable development. Handling this overwhelming data flow of information has to be done in an efficient way. Application of expert systems will be a great help to overcome this problem.

In conclusion, environmental requirements have to be mentioned.
Pollution prevention will play a dominant role in future design and operation of ships.
These subjects will of course have an important impact on the design of ship systems.
For example: At the moment propulsion control is tuned in a way to maximise fuel efficiency. In the near future the system will be tuned in a way to minimise pollution to the atmosphere.

5. CONCLUSIONS

It can be expected that the M-frigate of the Karel Doorman-class will operate in the future at least as efficiently and smoothly as the S-frigate of the Kortenaer-class do today. Moreover, the platform of the M-frigate wil have more redundancy levels in its control systems and a higher degree of performance and reliability.
M-frigate operators will have a deeper and wider control of the platform installations.
The efficiency of damage control management will be greatly improved. A 25 percent reduction in the number of platform control- and management engineers compared to the S-frigate has been realised.
Experiences with S-frigates and Walrus-class submarines have shown that with the Integrated Control and Monitoring System for the platform of the M-frigate, the Royal Netherlands Navy is "on track".

In Merchant shipping research the results of the efforts concerning the total integrated ship control from an Operations Centre, can be reviewed as acceptable and promising.
Still much work has to be done, especially in the direction of higher reliability, in general. Also environmental requirements will demand a prominent role in the near future.

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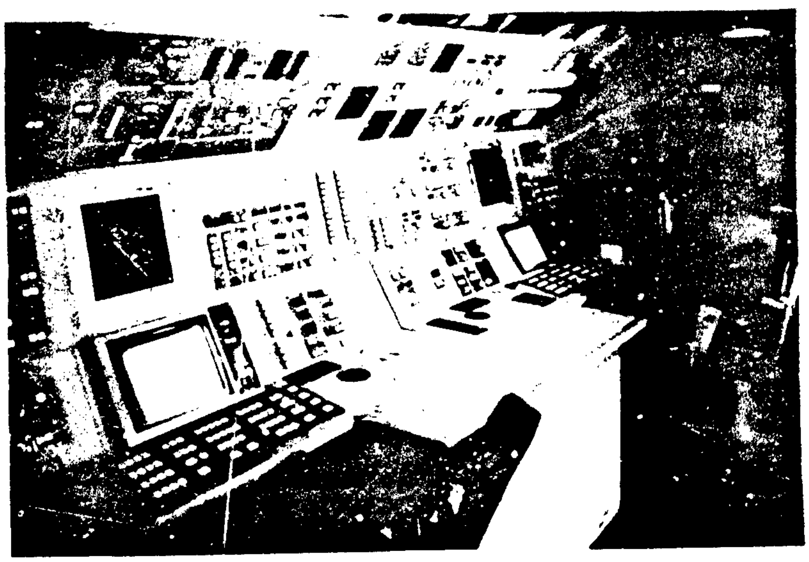

FIGURE 1   ICMS panel Walrus-class submarine

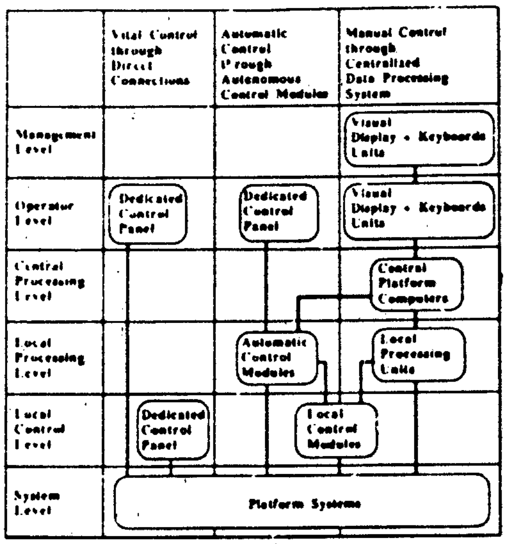

FIGURE 2 ICMS M-class frigate

FIGURE 3 SCC M-class frigate

"DESIGN CONCEPT FOR A FIBER OPTICS BASED DATA ACQUISITION SYSTEM FOR HM&E SHIP SYSTEMS"

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1. ABSTRACT

A concept design for the fiber optic transport of sensors' data for low data rate systems is presented. The concept is novel. All sensors in the sensor suite share a common optical data bus onto which they broadcast their respective data updates based solely on commands generated internally. No external queuing is required. As a consequence, inherent in the design schema is a "pathogen" that will occasionally manifest itself in the transmission of erroneous sensors' data. Inclusion in the design of a primitive signal conditioning algorithm is shown to dramatically lower the statistical frequency of data transport errors that are the symptoms of that pathogen. The resultant performance evidences such a low transmission error rate that the design's stochastic nature is rendered virtually deterministic.

2. INTRODUCTION

The control and monitoring systems for Hull, Mechanical and Electrical (HM&E) ship systems are typically comprised of three generic active components: sensors, processors, and effectors, and one generic passive component: cabling. The traditional medium for transporting signals between those active components is copper. The rationale is irrefutable. The generic active components transmit or receive electronic signals. The transport of those signals requires that the medium evidence high electrical conductivity, while the number of such signals mandates low cabling costs. Copper satisfies both criteria optimally. Efforts to apply fiber optics globally as a signal transmission medium for HM&E ship systems will prove unsuccessful unless copper's inherent cost advantage can be discounted sufficiently for the unique benefits of fiber optics to prevail in the trade-off analysis for medium selection. Those efforts must first focus on the transport of sensor signals. The reason is simple. The preponderance of signal cabling is chargeable to the transport of sensor signals to processors. A global technological upgrade from copper to fiber requires that the sensors' outputs all be optical.

The Navy possesses a host of qualified HM&E systems applicable sensors. These sensors feature a transduction element followed by an energy conversion stage, and are usually terminated with some signal conditioning electronics that provides the active electronic signal for copper medium transport to a processor. A fiber optic medium could be substituted by the relatively simple expedient of appending to what was the electronic output a specialized electronically-based stage, immediately followed by an optical transmitter fitted with a fiber optic "pigtail". The sensor would then present an optical interface, and thus call for a fiber optic medium for transport of its signal. In principle, each of the sensors in the sensor suite could be linked fiber optically to their host processors directly by means of individual, dedicated fiber optic cables, one each for each sensor. However, cost prohibits such an approach for the simple reason that each of the host processors must contain a complement of optical receivers that matches in number the sensor signals that that processor hosts. Clearly, a more affordable approach to signal transport is required.

Affordability of transport of all of the optical signals in a large sensor suite to their host processors mandates multiplexing. A time-division-multiplexing (TDM) approach is preferred to the alternative of frequency-division multiplexing (FDM). A FDM based signal management schema imposes stringent linearity requirements on the active optical components to accommodate even a very modest sensor suite. Component cost thus proves prohibitive. In contrast, TDM-based signal transport designs do not require linearity of optical components. As a result, they can in principle service a much larger sensor suite at a lower optical component cost. TDM is clearly the preferred choice.

There are a variety of TDM schemas in vogue for sensor data acquisition. Some are used widely in shipboard systems and others have only been proposed. One of the more sophisticated of those schemas features "smart" sensors, all connected to a sensor data bus that terminates on a processor. Date exchanges between the processor and the sensor are all "sink initiated". The sink is the processor. All sensor transmissions are initiated by the processor. The procedure is straightforward. If the processor elects to interrogate a particular sensor in the suite, it does so by transmitting over the bus the unique digital address of that sensor. All sensors receive that address, but only the sensor that has been pre-programmed with that unique address responds. The sensor's response is a "word" that is the digital equivalent of the parameter that that sensor transduces. If such a TDM schema were to be applied fiber optically, each of the sensors would perforce contain both an optical transmitter and an optical receiver, rendering the implementation costs comparable to the

non-multiplexed, or dedicated signal type data acquisition system and less desirable from an availability standpoint. The kev points here are that TDM schemas ranging from the most complex to the simplest all require a nominally equivalent suite of active optical hardware to implement, and the size of that suite renders the implementation costs excessive.

3. CONCEPT OVERVIEW

A substantive reduction in the size of the active optical hardware suite can be effected, but not without an attendant penalty. Suppose that the only active optical hardware in each sensor is an optical transmitter. The fiber pigtails from each of the sensors in the sensor suite can be linked to a common optical fiber via fusion couplers. That common optical fiber then becomes the sensors' fiber optic data bus. Control of the optical transmissions of each sensor is accomplished by electronic hardware resident entirely within that sensor. The sensors do not receive any external signal, including and especially a master clock signal or a sensor address signal. Accordingly, their transmissions are neither synchronized with each other, nor controlled asynchronously from an external source. Instead, each sensor transmits its distinct digital word quickly and periodically based on its own internal "clock". The transmission periodicities are nominally equal, and so too are the transmission durations. Evidently, there is a distinct probability of occasional overlap of one or more sensor transmissions, resulting in the propagation of erroneous signals from those sensors. That is the penalty to be paid in exchange for eliminating the need for any optical receivers other than the one required by the processor that interrogates the fiber optic bus. If the sensor data acquisition system can be engineered so as to make that penalty "acceptable", fiber is rendered a more affordable signal transmission medium.

Minimization of the probability of overlapping sensors' transmissions can be accomplished by minimizing the duration and maximizing the periodicity of those transmissions. Transmission durations of less than 1 usec are achievable. The maximum period of the transmissions are governed by the refresh rate requirement imposed by the processors. In ship engineering plants, the specified sensors data refresh period is not to exceed 250 msec. If each of the sensors in the suite broadcast their information onto the optical bus with a nominal periodicity of 125 msec (twice the processor mandated refresh rate), then the candidate schema proposed here for sensors' data acquisition guarantees that the data from every sensor in the suite is optically presented to the interrogating processor at least as often as once every 250 msec. The argument that supports that assertion is straightforward. In each 125 msec frame, all sensors in the suite transmit their information. However, the precise time in that frame that an

individual sensor transmits is arbitrary, or random. As a consequence, it is possible that a particular sensor in the suite could transmit at the start of a 125 msec frame. Accordingly, 250 msec is the least upper bound of the sensors data refresh rate. Because of that fact, the nominal periodicity of sensors' transmission is 125 msec, which makes available precisely 125,000 distinct transmission "windows" for the entire population of sensors in the suite, provided that 1 usec is allocated for the transmission duration for each sensor. With 125,000 distinct transmission windows, the probability that a particular sensor transmission will overlap the transmissions of one or more other sensors in the suite is rendered minimal for a fixed sensor population. What remains to be assessed is the odds that a particular sensor transmission will occupy its own distinct transmission window. Those odds are the quantification of the aforementioned penalty.

Suppose the population of the sensors in the suite is m. With 125,000 distinct transmission windows, the probability, P, that a particular sensor transmission will occupy its own distinct transmission window is related to m as follows.

$$P = \left(\frac{125{,}000-1}{125{,}000}\right)^{m-1} \simeq \frac{125{,}000-(m-1)}{125{,}000} \tag{1}$$

More specifically, suppose that m=50. Then P=0.999608, and the odds that a particular sensor transmission will not overlap one or more transmissions from other sensors in the suite is 2,550:1. While those odds are sufficiently favorable to conclude that the penalty is not too high to discount the design schema proposed here as a viable candidate for implementation, it cannot yet be safely asserted that design feasibility has been demonstrated. Successful design resolution of the issue of overlapping sensor transmissions is a prerequisite. Effective management of the sensor data by the interrogating processor is the key to resolving the issue of sensors' transmission overlap.

Suppose that there are 50 sensors in the suite, and 125,000 distinct transmission windows available for occupancy. The odds are 2,550:1 that the transmission of any one of the sensors in the suite will occur without overlapping the transmissions of one or more of the other 49 sensors. Postulate that the interrogating processor features an optical receiver that serially converts the optical digital "words" on the sensors' data bus into electronic digital data words that are then stored in the processor's memory. The memory location chosen for a particular digital word is governed by a unique six bit address that prefaces the ten bits of data that together define the sixteen bit word transmitted periodically by the sensor with that address. Let the interrogating processor be charged with the responsibility for

conditioning the sensors' data as a prerequisite for subsequent data transfer to "end-user" processors. Assume that the data are conditioned by an algorithm specifically formulated to virtually preclude substantive degradation of the conditioned data as a consequence of sensors' transmission overlap. How sophisticated need this algorithm be in order that it evidence the requisite performance potential? Surprisingly, the algorithm can be primitive, and yet very effective. However, the simplicity of the algorithm belies the complexity of the rationale upon which the assertion of its efficacy is based.

4. CONCEPT FORMULATION

The concept design features a suite of m optical sensors, each of which is linked to a single, common optical fiber through individual fusion couplers. The coupling ratios of those fusion couplers are all nominally equal and have been chosen so as to provide for maximum optical power transfer onto the single, common optical fiber that constitutes the sensors' data bus. Also linked to that data bus is an optical receiver that converts the optical digital words transmitted by the sensors into electronic digital words, each of which is stored in the memory of the bus interrogating processor. The durations of the sensors' transmissions are all equal and nominally periodic with period, Ts. However, the sensors are assumed to be engineered such that each of their transmissions occurs once every Ts seconds, but at a time within that interval that is random. Resident in the processor is the tactical software that serves to condition the received sensors' data before it is uplinked to end-user processors. The signal conditioning algorithm stores in m separate sections of memory L words, each every tspec/2 seconds, where tspec is the sensor transmission update period mandated by the end user processors. Each set of L words is associated with one and only one of the m sensors. The algorithm then counts the number of binary ones and zeros associated with each data bit in each of the L words. Whichever of those two states is represented most often is the one that the algorithm adjudicates as correct. In this way, the algorithm uses the data in all L words provided by a particular sensor to construct a single error-free word that is comprised of the binary address of that sensor and the correct data transmitted by that sensor. Since there are m sensors, the algorithm produces m such error-free words that, as a set, constitute the transmissions of all m sensors in the suite during the period, tspec/2. The set of m words are the data that the processor subsequently distributes to the end-user processors elsewhere in the system.

Transmissions of the sensors in the suite occur at random times within the interval, Ts. For that reason, there is a distinct probability that the transmissions of one or more sensors will overlap each other degrading the optical words associated

with those sensors. The validity of the optical information on the sensors' data bus is thus suspect. It is the signal conditioning algorithm within the bus interrogating processor that utilizes the L separate transmissions of each sensor to eradicate bit errors that attend sensors' transmission overlap. In view of the stochastic nature of the sensors' data, no algorithm can guarantee error-free sensor data. What is required, therefore, is a mathematical assessment of the probability that the algorithm will produce valid sensor data. If it can be shown that the algorithm can meet or exceed the inherent bit-error-rates (BER) of the active optical hardware, then the stochastic nature of the optical digital data bus design can be rendered transparent to the end-user processors.

The algorithm adjudicates differences between corresponding bits in each of the L words for each of the m sensors by counting the number of ones and zeroes associated with each of those bits. The more frequently occurring state is selected as the "correct" state. Since the algorithm's decision is predicated on majority rule, L is postulated to be an odd integer, but otherwise arbitrary. The efficacy of the algorithm is evidently very dependent on L. The larger the value of L, the higher the probability that the signal conditioning algorithm will produce error-free data words. However, an increase in L mandates a proportionate increase in the frequency of sensors' transmissions which, in turn, reduces the ratio of the number of available transmission windows to the number of sensors in the suite, thus increasing the probability of sensors' transmission overlap. The probability, Pg, that the transmission of a particular sensor in the suite will not co-occupy a transmission window is a function of the ratio of the transmission period, Ts, to the transmission duration, ts. Of course, Pg also depends on m.

$$P_g = \left[\left(T_s/t_s\right) - (m-1)\right] / \left(T_s/t_s\right) \tag{2}$$

L sensors' transmission periods, Ts, must occur within tspec/2 seconds if the signal conditioning algorithm is to meet the sensors' data update rate imposed by the end-user processors.

$$T_s = t_{spec}/2L \tag{3}$$

If equation (3) is used to eliminate Ts in equation (2), Pg will depend solely on the fixed number, tspec, and the two parameters: m and L.

$$P_g = 1 - 2L(m-1)\,t_s/t_{spec} \tag{4}$$

The probability that that transmission of that same sensor will co-occupy a transmission window is (1 - Pg), where:

$$1 - P_g = 2L(m-1)\,t_s/t_{spec} \tag{5}$$

Equations (4) and (5) provide two probabilities that could be regarded as the respective likelihoods of the outcome of the toss of a "loaded" coin. The problem of determining the requisite number of tosses, L, of the coin to ascertain which face of the coin, "heads" or "tails", is the preassigned favored result is notionally equivalent to the problem of selecting the requisite value of L to provide sufficient certitude that the processor's algorithm will indeed produce an error-free sensor data word. Suppose L tosses are postulated and the result of each toss is recorded. If L is odd, one of the two possible outcomes (heads or tails) will occur more frequently than the other. The problem of determining coin face bias empirically thus devolves to choosing that side of the coin that turned up more frequently than the other. Suppose heads were favored. Then as long as the total number of occurrences of tails were one less than one-half of the number of tosses, L, the correct conclusion is that heads was preprogrammed to occur more frequently than tails. Therefore, the processor algorithm can accommodate as many as (L - 1)/2 overlapping transmissions of a particular sensor and still produce an error-free construct of that sensor's data word.

The probability, P ([L-1]/2), of no more than (L-1)/2 overlapping transmissions in L transmissions for a particular sensor is related to Pg in accordance with the following truncated binomial series.

$$P([L-1]/2) = \sum_{i=0}^{\frac{L-1}{2}} \frac{L!}{(L-i)!\,i!}(P_g)^{L-i}(1-P_g)^{i} \tag{6}$$

The problem of determining L so as to render the stochastic nature of the bus transparent to end-user processors is mathematically equivalent to choosing L in equation (6) sufficiently large so that the contribution of the remainder of the binomial series is less than the optical hardware bit-error-rate (BER), typically

10^{-9}. Fortunately, the terms of the series are all positive, and the nature of the series is such that the (L-1)/2 term is an upper bound of the sum of all the succeeding terms.

Let Pj be the probability of exactly j overlapping transmissions of one sensor in a set of L transmissions. If it can be shown that the probability of more than j overlapping transmissions of one sensor in a set of L transmissions is less than or equal to Pj, i.e.:

$$P_j \geq \sum_{i=j+1}^{L} P_i \tag{7}$$

then the proof will be complete. The approach selected to prove the latter inequality is by induction. Accordingly, it must first be shown to be valid for a specific value of j and then proved for the (j + 1) case, assuming that it holds for the j case.

Let j = L - 2, then equation (7) is specialized and its series consists of only two terms.

where,

$$\left.\begin{aligned} &P_{L-2} \geq P_{L-1} + P_L \\ &P_{L-K} = \frac{L!}{K!(L-K)!}(P_g)^K(1-P_g)^{L-K} \end{aligned}\right\} \tag{8}$$

If the second of equations (8) is substituted into the first and the result solved for Pg, then Pg will be constrained to satisfy the following inequality.

$$P_g \geq \frac{L-2+(3L^2-2L)^{1/2}}{(L-1)(L+2)} \tag{9}$$

Equation (9) represents one of what will prove to be two constraints that Pg must satisfy to render equation (7) valid. The second constraint emerges from the second portion of the induction process that calls for equation (7) to be the principal postulate in the proof that equation (7) also holds when the index, j, is decremented by one. Assume that equation (7) holds for j = L - K. If equation (7) is to be valid for j = L - K - 1, and P_{L-K} dominates the sum of the Pi from (L-[K-1]) to L, then

$$P_{1-(K+1)} / P_{L-K} \geq 2 \tag{10}$$

The second of equations (8) can be used in conjunction with equation (10) to show that:

$$P_g \geq \frac{2}{2 + \frac{L-K}{K+1}} \tag{11}$$

which for L - K = (L-1)/2 yields the requisite constraint on Pg for the (L-1)/2 term in equation (6) to dominate the probability of more than (L-1)/2 overlapping transmissions for a sensor in a set of L transmissions. Fortunately, the values of Pg and L that provide the greatest sensor population permitted for a fixed BER call for values of Pg that satisfy both equations (9) and (11), thus validating the assertion that the last term in the series in equation (6) dominates the entire remainder.

Choose L such that the (L-1)/2 term contribution to the probability of a valid data word construct by the algorithm is less than the hardware BER of 10^{-9}. Then, the stochastic nature of the optical bus will lead to data transfer errors that are less frequent than those chargeable to the active optical components used for implementation. The design criteria that must be satisfied for the bus to perform as if it were deterministic thus devolves to constraining L such that the last term in the series for P([L-1]/2) is bounded above by 10^{-9}.

$$\frac{L!}{\left(\frac{L+1}{2}\right)!\left(\frac{L-1}{2}\right)!}\left(P_g\right)^{\frac{L+1}{2}}\left(1-P_g\right)^{\frac{L-1}{2}} < 10^{-9} \tag{12}$$

L is assumed to be odd and Pg and (1 - Pg) are given respectively by equations (4) and (5). If the latter equations are used to eliminate those two probabilities from equation (12), the design criteria is expressed in terms of fundamental parameters.

$$\frac{L!}{\left(\frac{L+1}{2}\right)!\left(\frac{L-1}{2}\right)!}\left(1-\frac{2\tau_s L(m-1)}{\tau_{spec}}\right)^{\frac{L+1}{2}}\left(\frac{2\tau_s L(m-1)}{\tau_{spec}}\right)^{\frac{L-1}{2}} < 10^{-9} \tag{13}$$

Suppose a BER of value "BER" is postulated for the data transfer schema. Then the inequality sign in equation (13) can be replaced by an equality sign with the substitution of BER for the upper bound, 10^{-9}. The result is an implicit equation for the sensor population, m, as a function of the design parameter, L, and the "fixed" parameters: ts, and tspec.

$$BER = \frac{L!}{\left(\frac{L+1}{2}\right)!\left(\frac{L-1}{2}\right)!}\left(1-\frac{2\tau_s L(m-1)}{\tau_{spec}}\right)^{\frac{L+1}{2}}\left(\frac{2\tau_s L(m-1)}{\tau_{spec}}\right)^{\frac{L-1}{2}} \tag{14}$$

Equation (14) is a transcendental equation that evidences an extremum. Note that the BER is comprised of three factors: two monomials and a ratio of factorial functions. For modest values of L, the monomials are the principle determinants of the BER, whereas for larger values of L the ratio of factorial functions becomes the chief contributor to the BER. There exists, therefore, a unique value of L that will permit the largest value of m for a fixed value of the BER. Unfortunately, the transcendental nature of the factorials poses a problem in attempting to solve explicitly for m as a function of L and the BER. If, however, Stirling's approximation is employed for each of the three factorials that form the ratio of factorials, the problem of solving directly for m is rendered a more tractable proposition. The application of the approximation is restricted to modest and large values of L. The latter assumption is invoked and equation (14) is then replaceable by the following resultant.

$$BER \simeq 2^{L}\left(\frac{2}{\pi L}\right)^{\frac{1}{2}}\left(1-\frac{2t_sL(m-1)}{t_{spec}}\right)^{\frac{L+1}{2}}\left(\frac{2t_sL(m-1)}{t_{spec}}\right)^{\frac{L-1}{2}} \qquad (15)$$

Equation (15) can be used to solve for m explicitly provided that a second assumption is also valid, namely:

$$\frac{2t_sL(m-1)}{t_{spec}} \ll 1 \qquad (16)$$

Accordingly,

$$\left(1-\frac{2t_sL(m-1)}{t_{spec}}\right)\left(\frac{2t_sL(m-1)}{t_{spec}}\right) \simeq \left[\left(\frac{\pi L}{2}\right)^{\frac{1}{2}} BER\, 2^{-L}\right]^{\frac{2}{L-1}} \qquad (17)$$

Equation (17) can be viewed as a quadratic in m.

$$m \simeq 1+\frac{t_{spec}}{4t_sL}\left[1-\left(1-4\left[\left(\frac{\pi L}{2}\right)^{\frac{1}{2}} BER\, 2^{-L}\right]^{\frac{2}{L-1}}\right)^{\frac{1}{2}}\right] \qquad (18)$$

The maximum value that m can attain for a fixed BER depends not only on L, but the parameters: tspec and ts as well. Assume that the specified update rate, tspec, is 250 msec, and that ts is 1 usec. The BER typical of active optical hardware is nominally 10^{-9}. If the stochastic nature of the bus is to be rendered virtually transparent to the end-user processors, then its component BER should be selected to be at least an order of magnitude smaller. Consequently, let BER = 10^{-10}, and substitute that value for the BER and the other values suggested for ts and tspec all in equation (18). If the resulting equation is then solved for m for a wide variety of values of L, there results a specific numerical relationship between m and L, which evidences a peak value of approximately 295 for m at L=53. Consequently, from a

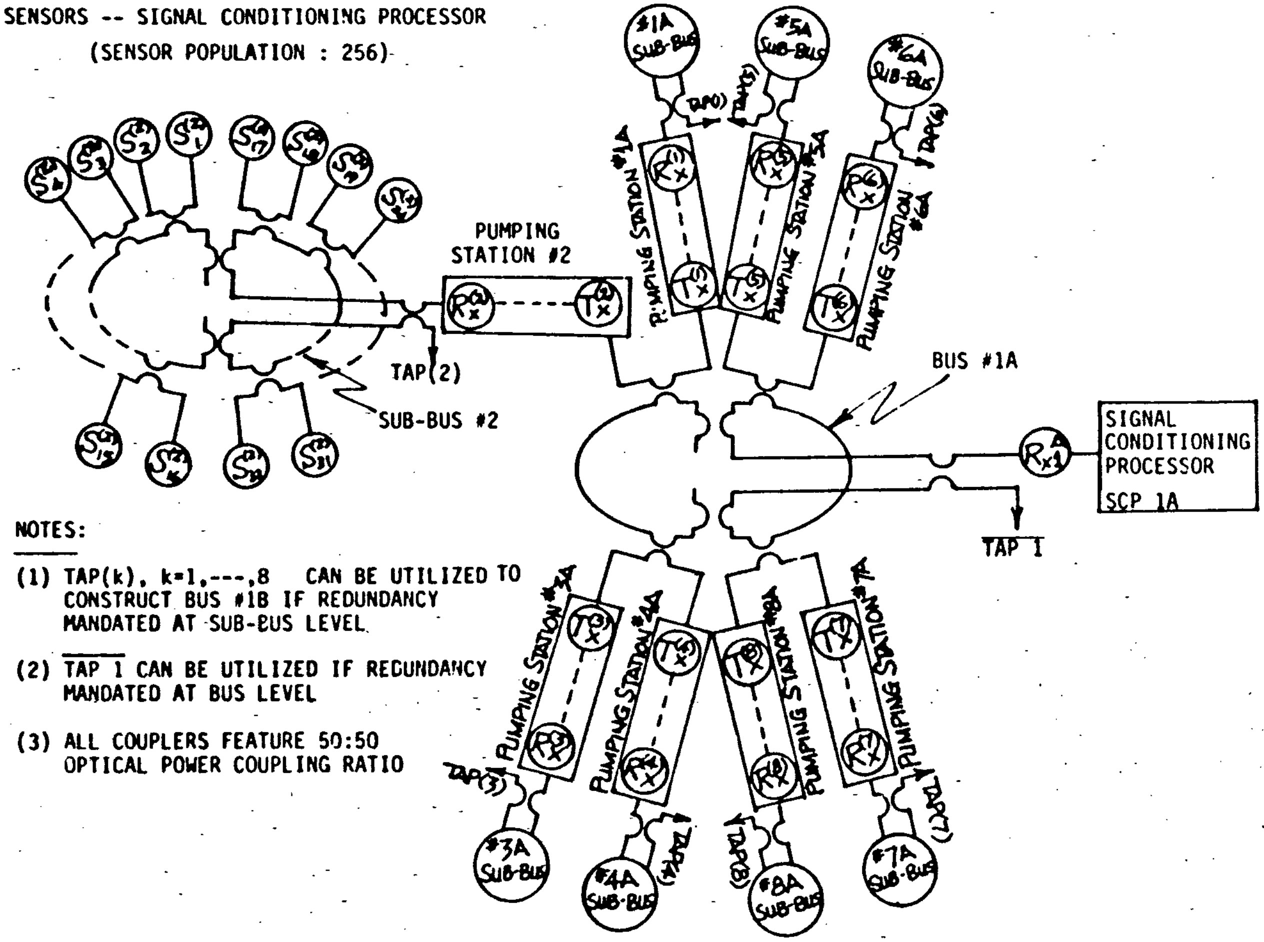
theoretical, standpoint, as many as 295 separate sensors can be accommodated on one optical fiber. A population of sensors that large would mandate at least a nineteen bit sensor word. With a requirement of 53 iterations of the signal conditioning algorithm for every 250 ms, the minimal size of the active working memory required would be a modest 300K bits of random access memory (RAM). Assuming a total sensor complement of 1000 sensors for the entire ship's engineering plant, only four separate (but identical) signal conditioning processors would be required to service the entire plant! Their memory requirements are modest; their tactical software would be simple; and they would all be identical.

The foregoing analysis demonstrated that it is theoretically possible to multiplex almost 300 individual sensors onto a single fiber via the proposed schema. However a population of that size would impose particularly severe sensitivity and dynamic range requirements on the signal conditioning processor's optical receiver and at the same time would mandate extraordinarily high optical outputs from the sensor's optical transmitters. In short, it may be the optical power budget, not the statistical nature of the bus, that limits sensor population. One possible configuration that could be used to implement the proposed schema is shown in Figure 1. Here a population of 256 sensors is managed by a single signal conditioning processor. Eight distinct subsets of thirty-two sensors each are optically coupled onto a common fiber that is in turn optically linked to a signal conditioning processor. Each set of thirty-two sensors possesses its own distinct "sub-bus" and "pumping station" that raises the intensity of the optical pulses on that sub-bus to provide sufficient optical signal power to the main or common bus. The decision to limit the number of sensors to thirty-two in each subset was based on the assumption that single-mode fiber was to be used for all signal transmissions. In that event, discounting fusion coupler and splice losses and assuming 50:50 coupling ratios, the nominal optical power loss between the "most remote sensor" and the pumping station receiver is 30 db. Assuming that the output power of the transmitters in each sensor is -21 dbm, the sensitivity of the pumping station receiver must be higher than -51 dbm. The dynamic range must exceed 21 db, again discounting coupler and fusion splice losses. Close inspection of the configuration will disclose the fact that the pumping station receiver sensitivity requirement can be relaxed by the simple expedient of reducing the number of sensors per subset. If it is also required that the total number of sensors (256) be maintained constant, this too can be achieved despite the reduction in the subset population. Simply construct one or more additional subsets of sensors. In principle, the maximum number of sensors supportable by the configuration depicted in Figure 1 is N^2, where N is the number per subset. This candidate implementation schema provides sufficient

OPTICAL BUS STRUCTURE

SENSORS -- SIGNAL CONDITIONING PROCESSOR

(SENSOR POPULATION : 256)



NOTES:

(1) TAP(k), k=1,---,8 CAN BE UTILIZED TO CONSTRUCT BUS #1B IF REDUNDANCY MANDATED AT SUB-BUS LEVEL.

(2) TAP 1 CAN BE UTILIZED IF REDUNDANCY MANDATED AT BUS LEVEL

(3) ALL COUPLERS FEATURE 50:50 OPTICAL POWER COUPLING RATIO

FIGURE 1. OPTICAL BUS STRUCTURE

flexibility to at once satisfy both the schema's requirements and the limitations of the optical hardware. Communications between the signal conditioning processor and the end-user processors are all space division multiplexed and feature the unidirectional transport of signals from the signal conditioning processor to the end-user processors. Communications between sensors and the original signal conditioning processor and between that processor and the end-user processors are all source initiated. For that reason, the design in no way limits the number of end-user processors.

5. HARDWARE DESIGN

The proposed schema was based on the assumption that the sensors were all of the analog variety. There is, however, a significant complement of discrete type sensors in HM&E systems. It would prove costly to outfit each of those discrete sensors with the same electronic and optical hardware assumed to be resident in the analog optical sensors. Instead, the information available in ten or less discrete (two-state) devices can be "packaged" into a single ten bit data word which can be appended to a single, unique address word to provide one "sensor word". One approach to implementation is to provide a parallel array of up to ten dedicated signal conditioner input channels, one each for each discrete sensor. In this way, all discrete signals can be formatted in an electronically identical manner to provide one ten bit data word that can be loaded, along with its unique address, into a parallel to serial converter. The design of subsequent stages can be made identical to the corresponding stages required for the transport of analog type signals. Consequently, the task that remains to be accomplished in documenting the concept design presented here is to define the functional characteristics of each of the stages of networks that must be appended to the existing Navy qualified sensors.

Figure 2 depicts, in block diagram format, the several stages that comprise an analog sensor's network. Note that each sensor possesses its own distinct transduction element followed by a signal conditioning stage that provides a 0-10 VDC analog format. The analog output from that stage is coupled to the input of a ten bit parallel A/D converter, the output of which is digitally merged with a unique nine bit address to form a nineteen bit sensor word. The nineteen bit sensor word is stored in a parallel to serial buffer stage where it awaits an output command from a random number generator. Upon receipt of that command, the parallel to serial buffer drives the input to the sensor's optical transmitter, thus completing one sensor transmission. The only somewhat novel function evidenced in the entire digital suite resident in the sensor is the random number generator.

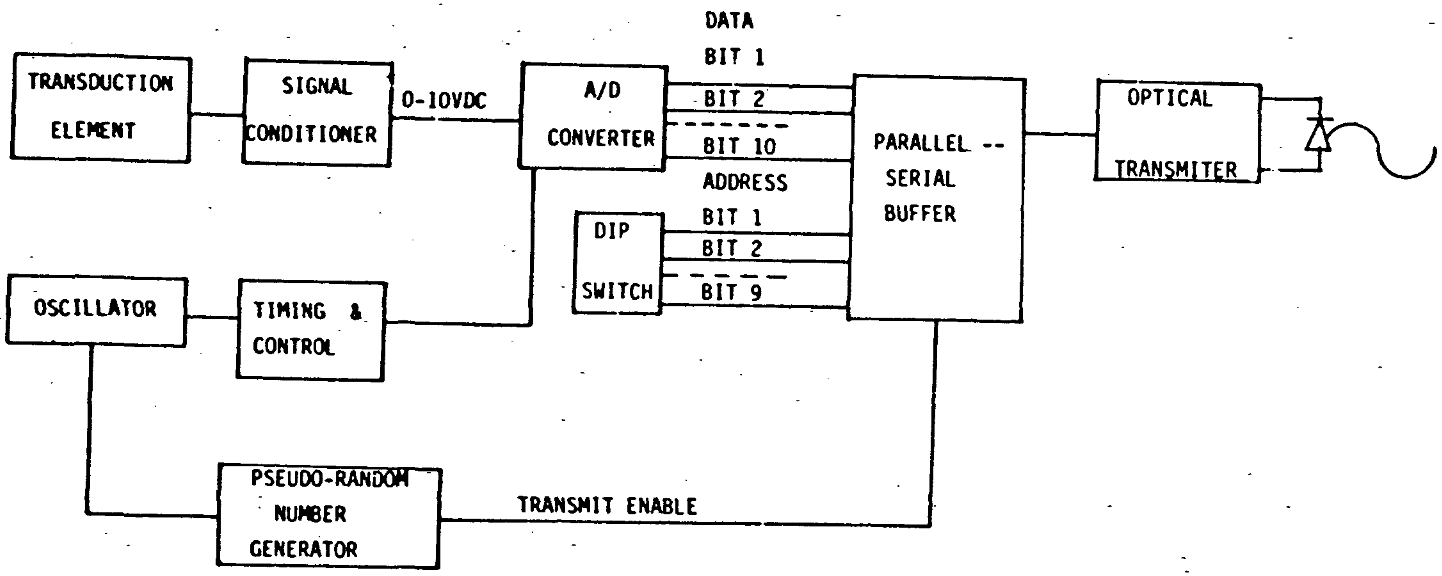


FIGURE 2 BLOCK DIAGRAM ARRANGEMENT OF A SENSOR'S HARDWARE SUITE

Implementation of a number generator that is truly random poses an irresolvable problem. However, a host of pseudo-random generators could be conjured, but all would perforce exhibit some inter-sensor correlation. The design imperative is one that calls for a pseudo-random number generator that provides relatively low inter-sensor correlation and yet evidences implementation tractability. One candidate approach that may satisfy both requirements is depicted in Figure 3. Here a high frequency oscillator drives the input to a cascaded array of up-counters. The duration of the count is nominally the ratio, 125 msec/L, where L is the number of signal conditioning algorithm iterations per uplink to the end-user processors. At the conclusion of up-counter iterations, the output of the cascaded up-counter array is summed with the unique digital address of the sensor in which it resides. The summand then serves as both the new initial value for the up-counter cascaded array and the input to a cascaded array of down-counters, the output of which is a single pulse of duration: 1 usec. During that pulse, the sensor's parallel to serial buffer is ordered to output its contents to the sensor's optical transmitter. The decision to recommend such a configuration for consideration was not solely based on the requirements to achieve tractability and low inter-sensor transmission correlation. Another issue also influenced that decision.

Suppose a significant fraction of the sensors were to transmit almost simultaneously with the result that their transmissions overlapped. The probability that the subsequent transmissions of those sensors would be characterized by sufficient time dispersal so that virtually all would select distinct transmission windows is low. Such a pathological scenario will occur. When it does, a dispersal mechanism could mitigate against the net adverse effects that the next few transmissions would have on the validity of the data words constructed by the signal conditioning processor. That mechanism is provided in the candidate pseudo-random number generator through the addition of the unique sensor address with the output of the first cascaded array of up-counters. If all of the corresponding hardware in all sensors performed absolutely identically and all sensors were to share the same transmission window, then what renders their next transmissions all non-overlapping is that addition of their unique addresses. In effect, the transmission of each sensor is caused to "drift" at its own distinct rate through all of the available sensor transmission windows, thereby promoting rapid recovery from those inevitable occasions when a significant fraction of the sensors' transmissions are contemporaneous. There is an attendant penalty, however. While the inclusion of that dispersal mechanism may produce early exit from pathological system performance, it may also increase the probability of occurrence of such anomalous behavior. Fortunately, the data shown in Figure 4 indicates that a major reduction in BER can be achieved at very modest reductions

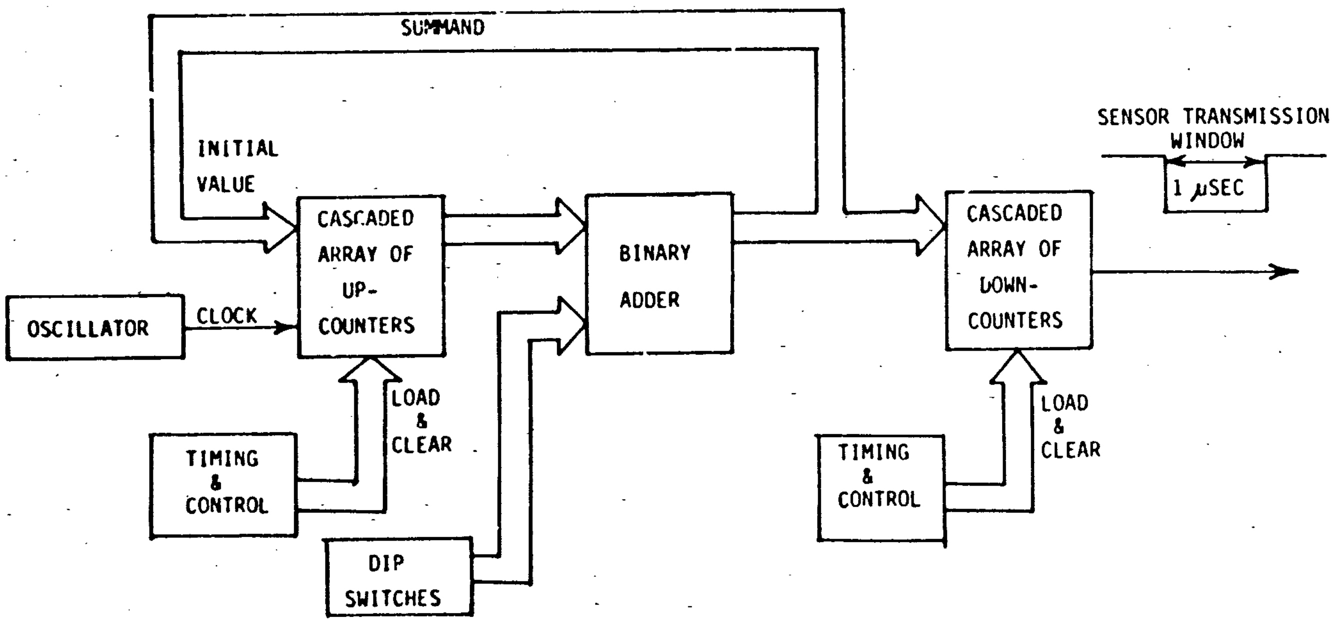


FIGURE 3 BLOCK DIAGRAM ARRANGEMENT OF A SENSOR'S PSEUDO-RANDOM NUMBER GENERATOR

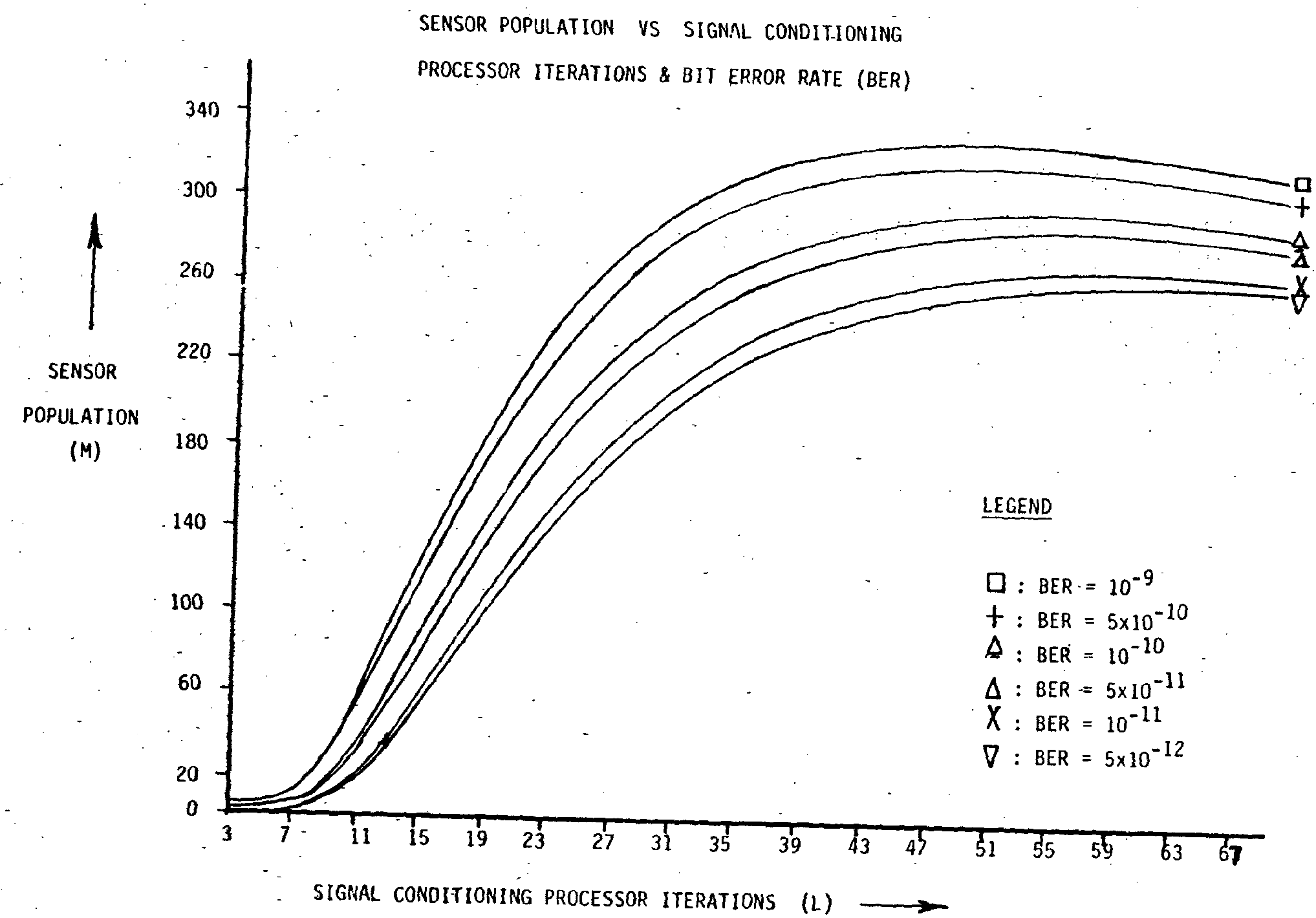


FIGURE 4 SENSOR POPULATION VS SIGNAL CONDITIONING PROCESSOR ITERATIONS

in sensor population, thus providing a powerful "tool" to offset the higher frequency of pathological system performance that may result from the inclusion of the dispersal mechanism.

Substantial change must be made to Navy qualified sensors to render them compatible with the proposed data transfer schema. Those changes would prove far too costly and lead as well to inordinately large sensor packages if the hardware required to effect those changes were to be constructed directly from single function, general purpose "chips" and "off-the-shelf" optical transmitters. The only practical alternative is to develop one special purpose integrated circuit that provides all or almost all of the sensors' timing and control functions. One standardized design for that specialized multi-function "chip" can be developed and integrated into all sensors. Furthermore, suppliers of optical transmitters have designed rather elaborate suites of support electronics for their transmitters. Those support electronics packages provide some functions that are no doubt recommended for retention for this application, while others may not be required. In short, consideration should also be given to customizing the optical transmitter with a view toward reducing the optical transmitter package. With all timing and control functions provided by a single chip and the optical transmitter package abbreviated to the maximum extent advisable, neither the size nor the cost of the sensors' augmentation hardware suite will prove impractical.

6. CONCLUSIONS

Navy qualified sensors used in HM&E ship systems can be modified to provide optical signal outputs. Those optical outputs can all be linked to a common fiber, or optical data bus. Transmission timing and control for each sensor can reside entirely within that sensor. No common control is required. A sensor data transmission is source (sensor) initiated. No source/sink protocol is required. The sensor suite of an entire ship's engineering plant can be comfortably and economically accommodated. More modest suites can be managed equally successfully. One sensors' data acquisition system design can host any one of a manifold of different control and monitoring systems architectures. No special requirements or design limiting constraints are imposed on the host and multiple hosts can be serviced simultaneously.

DIGITAL MONITORING AND CONTROL CONCEPT
FOR A MARINE GAS TURBINE

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1. ABSTRACT

This paper describes the conceptual design of a microprocessor-based full authority monitoring and control concept for an aero-derivative P&W FT4A-2 marine gas turbine engine. A notable feature of this engine controller is a digital fuel control system concept more suited to a marine propulsive application than the airborne designed hydromechanical fuel control unit presently fitted on this engine on Canadian Navy DDH 280 Destroyers.

An overview of the digital fuel control strategy, engine fuel system design modifications, engine monitoring and sequencing functions, and emergency engine operating considerations is presented to outline the full-authority concept.

The engine controller concept can be adapted to other marine gas turbine engines that the Canadian Navy will operate in the foreseeable future, in particular the GE LM2500 gas turbines installed on the Canadian Patrol Frigates (CPF).

2. INTRODUCTION

Gas turbines for marine propulsion are normally derived from airborne engines where the nozzle is replaced by a freely rotating gas generator. The hydromechanical control systems which control the engine fuel flow and variable geometry for these engines are normally retained because of their demonstrated reliability in aircraft applications.

The Canadian Navy has however concluded that a logical step forward in the evolution of marine gas turbine control systems [1] is the integration of fuel control and variable geometry control logic within a digitally based system which interfaces to and controls the fuel metering and variable geometry positioning equipment. Replacing the hydromechanical control system is favoured on the basis of operational and maintainability considerations. In marine applications, the hydromechanical control systems have not always faired well because the quality of fuel

has been a problem and setting up and maintaining the systems has been less than ideal.

In addition, the hydromechanical control systems on aero-derivative gas turbines have been designed to ensure optimum performance for an aircraft, which in most cases is well in excess of marine transient performance requirements. It was therefore concluded that the fuel control logic should also be re-designed to limit the engine to the slower transient response requirements of the marine application. This was considered to be desirable because it increases the engine's surge and flameout safety margins providing an inherently safer system.

The Canadian Navy thus commissioned an investigation to examine the feasibility of converting the hydromechanical fuel and variable geometry control systems of the aero-derivative gas turbines to digital systems while retaining mechanical equipment solely for metering the fuel and positioning the variable geometry. Based on the results of the feasibility study, the Navy decided to initiate the development of a prototype digital fuel controller for a P&WA FT4A-2 gas turbine to prove the concept. This is a 25000 hp gas turbine with fixed engine geometry. It serves as the main engine in a COGOG arrangement on the Canadian Navy's DDH280 class of warship (Figure 1).

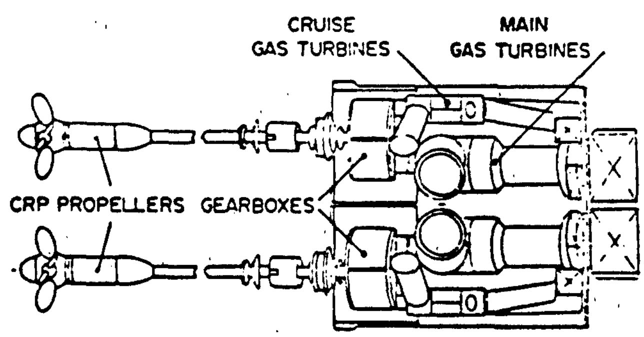


Figure 1: DDH 280 Propulsion Machinery Arrangement

The scope of the prototype was broadened to become a full authority Engine Control Module (ECM) encompassing engine sequencing, monitoring and protection as well as fuel control logic. A conceptual design has been completed and is the subject of this paper.

3. ECM FOR THE FT4A-2 MARINE GAS TURBINE

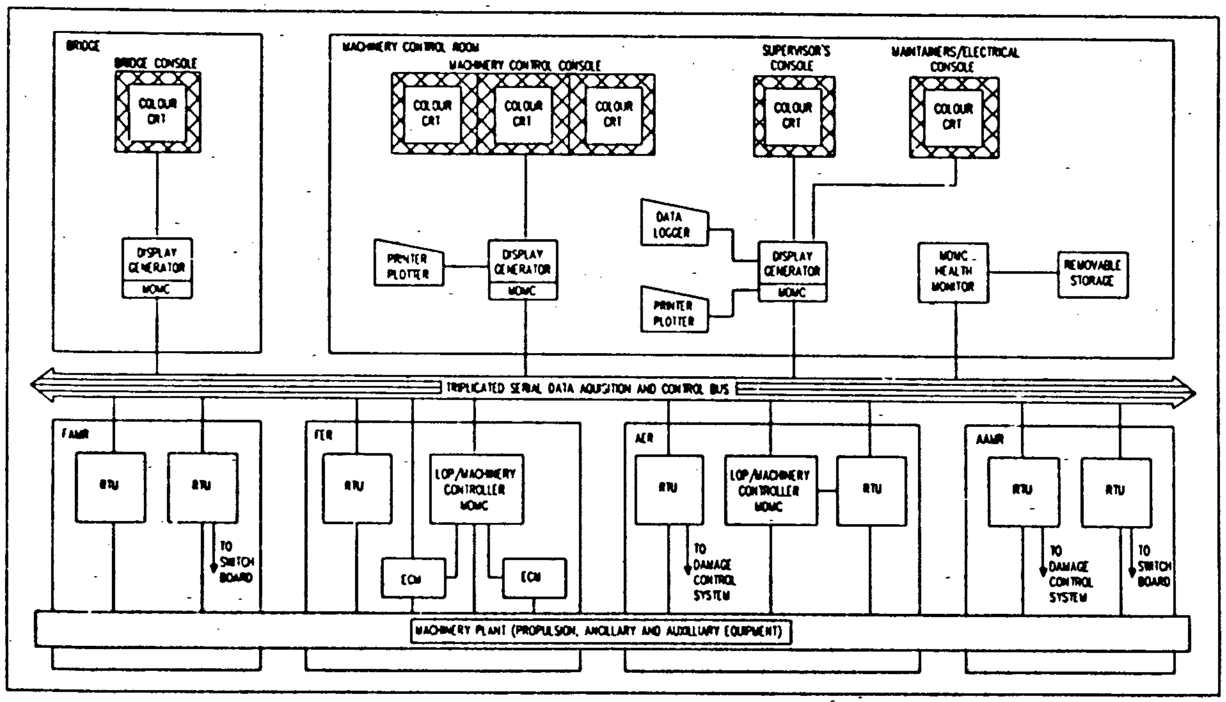
The intended application for the ECM is to control and monitor the FT4A-2 on the DDH280 class warship. These ships are currently undergoing a mid-life refit under the Tribal Class Update and Modernization Program (TRUMP). As part of TRUMP, the ships are being fitted with an Integrated Machinery Control System (IMCS) which is responsible for all propulsion machinery control. The TRUMP IMCS will be similar in configuration to the CPF IMCS which is illustrated in Figure 2. The ECM was designed as a unit controller which would interface to the IMCS. The functions included in the ECM cover command and feedback processing, engine monitoring and protection, fuel control, and engine sequencing. These functions were all designed taking into account the requirements of a warship application. With minor adjustments, however, the ECM can be used to control and monitor the FT4 in other similar applications.

The most important and complex function provided by the ECM is the control of fuel flow to the engine. A new digital fuel control strategy for the FT4 has been developed. The design of this fuel control function calls for a few modifications to the existing FT4 fuel system. Among other things this includes the removal of the hydromechanical fuel control unit (FCU) and the introduction of a simple fuel metering valve with its own actuator. With this design, metering of fuel to the engine is controlled digitally by the ECM.

The implementation of the ECM requires that it be interfaced to higher level controllers (HLC) as well as to the engine and its ancillaries. This is illustrated in the block diagram shown in Figure 3. The HLC is either the TRUMP IMCS or a Local Operating Panel (LOP). There is a signal conditioning interface between the ECM and the engine and its ancillaries. The interface is shown separately in Figure 3 but it can be considered to be part of the ECM. Control signals communicated from the signal conditioning interface to the engine and its ancillaries can be switched out and signals from an emergency control panel switched in thus providing the capability for reversion to a truly manual control mode.

The remainder of this paper will summarize the conceptual design of the ECM. The following matters relating to the design will be discussed.

- digital fuel control design
- engine fuel system design
- ECM logic design
- emergency engine operation



LEGEND -

CRT - CATHODE RAY TUBE
RTU - REMOTE TERMINAL UNIT
ECM - ENGINE CONTROL MODULE
LOP - LOCAL OPERATING POSITION
MDMC - MILITARIZED DIGITAL MICRO-COMPUTER

FAMR - FORWARD AUXILLIARY MACHINERY ROOM
AAMR - AFTER AUXILLIARY MACHINERY ROOM
FER - FORWARD ENGINE ROOM
AER - AFTER ENGINE ROOM

Figure 2: CPF Integrated Machinery Control System

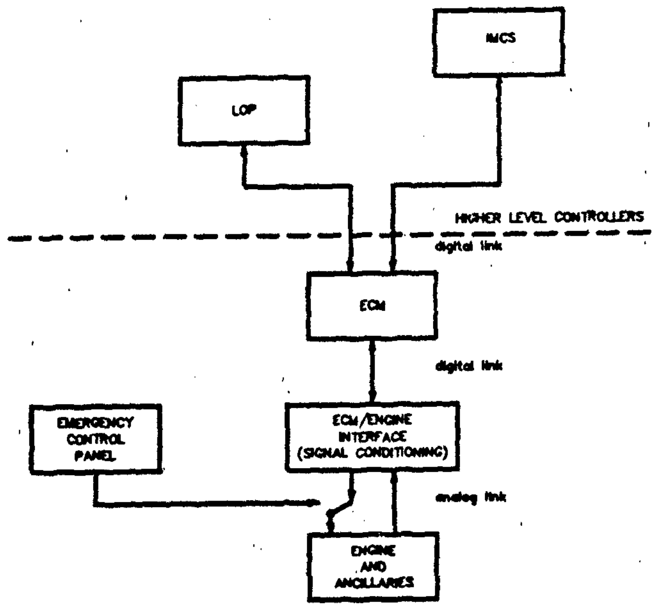


Figure 3: Overview of Engine Control Module

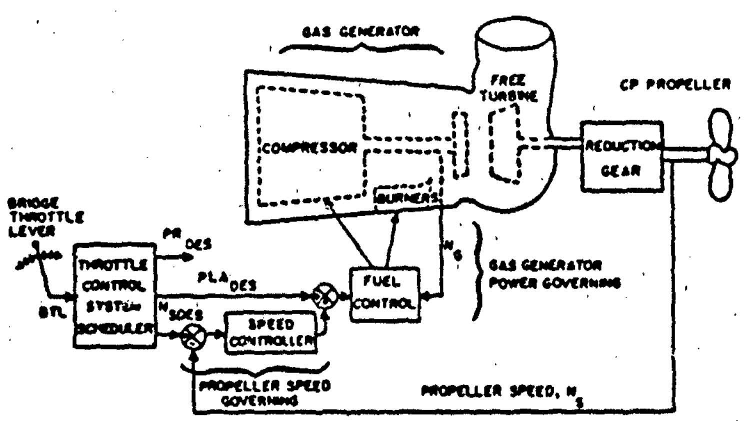


Figure 4: Closed Loop Propulsion Control

4. DIGITAL FUEL CONTROL DESIGN

4.1 Inner Loop or Outer Loop Control

Ship propulsion control systems of marine gas turbines are typically combinations of open loop gas generator power governed and close loop propeller speed governed systems as illustrated in Figure 4. The advantages and disadvantages of each governing system are still under debate [2,3] with respect to ship performance, machinery loads and the influence of sea state disturbances; nevertheless, a combination of both schemes has generally yielded acceptable manoeuvering performance to date.

In the context of a marine application such as the FT4 engines on board the DDH 280, the demanded power will generally be provided by the propulsion machinery control system (IMCS). In such an application there are two basic alternatives to the division of control functions between the propulsion control logic of the IMCS and the engine control logic of the ECM with respect to the control of engine power.

The first alternative is to have the ECM control fuel flow in response to a demanded power turbine speed input from the IMCS. The demanded power turbine speed is directly proportional to the desired propeller speed.

The second alternative is to have the ECM control fuel flow in response to a demanded gas generator speed (power) which is input from the IMCS. In this configuration the power turbine speed, and hence propeller shaft speed, is controlled by the IMCS. That is, the ECM provides an inner loop control for the gas generator while the IMCS provides the outer loop control on the power turbine speed.

The ECM uses the second alternative for fuel control. This is the traditional approach and is considered to be the better selection because in this configuration the IMCS is capable of independently relaxing its requirements for achieving a desired power turbine speed. This is important because under conditions of fluctuating load torque (heavy seas) it may be desirable to run the gas generator at a constant speed and let the power turbine speed vary so as to avoid unnecessary cycling of the gas generator. It also provides the advantage that it is consistent with the philosophy used by the propulsion control systems of existing gas turbine powered warships in the Canadian Navy.

4.2 General Description

A block diagram illustrating the ECM fuel control function is shown in Figure 5.

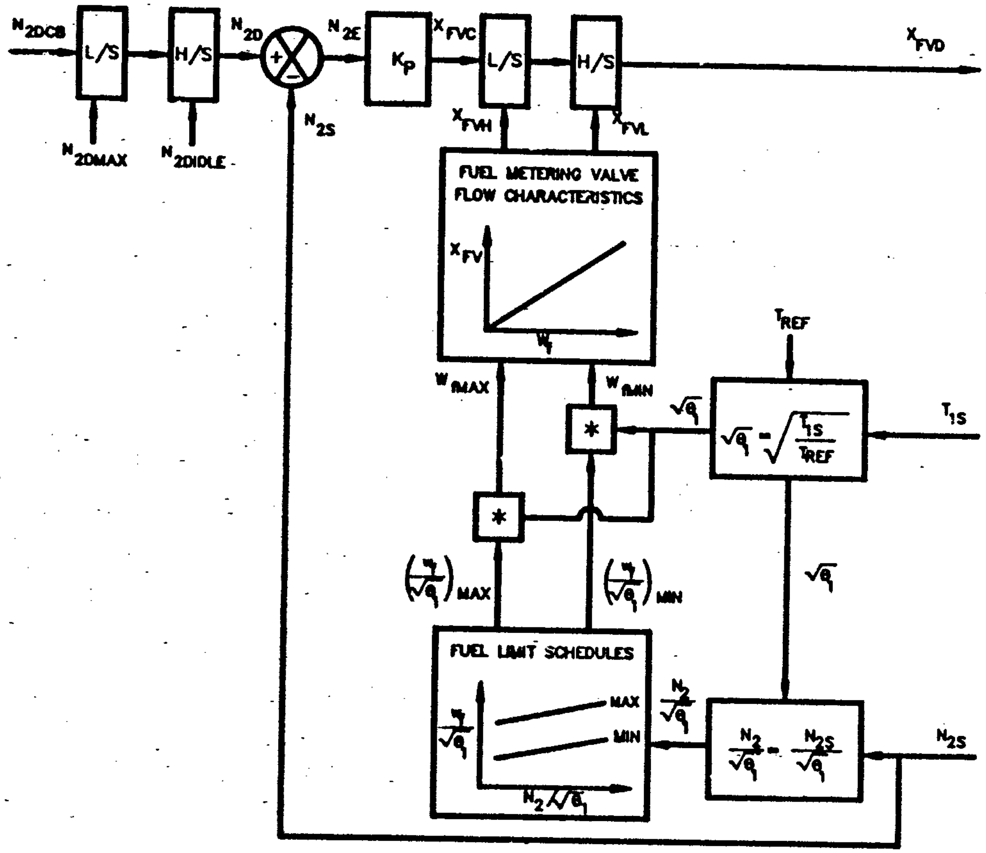


Figure 5: ECM Fuel Control Function

The ECM fuel control function must of course interface with the engine fuel system and instrumentation. Where possible existing components of the fuel system and the engine instrumentation were specified as part of the design. However, some changes to the fuel system were required. These are described in Section 5.

The fuel control algorithm basically consists of a simple N_2 droop governor with a fuel limit schedule cast in the form $W_f/\sqrt{\theta_1} = f(N_2/\sqrt{\theta_1})$.

The input to the ECM fuel control function from the HLC is simply gas generator HP spool speed demand, N_{2I}. This demand is conditioned before it is used to control the fuel flow. This involves transferring the input value to a cutback demand variable, N_{2DCB}. Circumstances may arise where the ECM must cutback the power (see Section 6.3) to protect the engine. This is done by manipulating N_{2DCB}. This value is then limited to between the minimum (idle) and maximum allowable, to obtain the droop governor demand, N_{2D}, as shown in Figure 5.

Inputs from the engine sensors are used to obtain the values of compressor inlet temperature, T_{1S} and gas generator HP spool speed, N_{2S}. These values are used to determine the corrected parameters $\sqrt{\theta_1}$ and $N_2/\sqrt{\theta_1}$. These parameters are then used to determine the maximum and minimum fuel flow based on the limits imposed by the fuel schedule.

Using the fuel metering valve flow characteristics, valve positions corresponding to the maximum and minimum fuel flow are obtained. These are used to limit the fuel valve position demanded by the droop governor. The output of the fuel controller is then, the demanded fuel metering valve position, X_{FVD}.

4.3 Update Rate and Sensors

The ECM must execute the fuel control function continuously. The frequency, or update rate, of this function must be selected so that it imposes the least processing burden possible while still providing stable and accurate control. Through the use of computer simulation it was found that an update rate of 10 Hz was adequate. The major contributing factors in the selection of the update rate were the effect of the droop governor proportional gain and the fuel valve actuator response. Sensor accuracy also had an impact on the selection.

The ECM requires a feedback of N_2, T_1, and fuel valve position, X_{FV}, from the fuel metering valve actuator. The valve position feedback is used to provide a measure of the fuel flow. This is only required for fuel schedule calibration and for

feedback to the HLC. It is not used to actively control the fuel metering valve position.

4.4 Fuel Metering

Controlling the flow of fuel to the combustion chamber of a gas turbine generally involves the use of a fuel metering valve. The fuel metering valve position and the pressure drop across it determines the amount of fuel that is metered to the engine. There are essentially three ways of controlling the flow [4]. One method is to place a flowmeter downstream of the fuel metering valve and to use the feedback from this device to close the loop when positioning the valve. With this method the pressure drop across the valve typically varies as the flow varies. A second method is to use a pressure control valve which bypasses flow so that a constant pressure drop across the metering valve is achieved. Control of fuel flow is then simply a matter of controlling the position of the fuel metering valve. This of course requires prior knowledge of the valve flow characteristics (flow as a function of valve position and pressure drop). A third method is a variation of the second method where both the metering valve position and the pressure drop across the valve are modulated according to some suitable algorithm.

The second method was selected for the ECM. This method of metering fuel is by far the most popular method used in gas turbine fuel controls. It has been developed over a number of decades and is in widespread use in both airborne and industrial applications. The existing FT4 hydromechanical FCU employs this method as an example.

The advantage of this design over one involving flowmeter feedback lies in its simplicity. The need for a flowmeter is removed thus reducing the number of components in the fuel system. The use of an accurate fuel metering valve provides the advantage that it can be used to both meter the fuel flow to the engine as well as provide a measure of the flow. Also, the fuel control function of the ECM is simplified because logic to close the loop on fuel flow while controlling valve position is not required. This improves the reliability of the system because the fuel control logic does not rely on a measure of fuel flow, other than for calibration purposes. The third method of metering fuel was not considered owing to the added complexity in terms of hardware and control logic required to control both valve position <u>and</u> pressure drop across the valve.

The performance characteristics of the fuel metering valve and actuator were not defined in this conceptual design. However, estimates of typical characteristics were used when performing any design calculations or computer simulation studies.

It should be noted that the steady state accuracy of the fuel metering valve and actuator is not critical. This is true because the ECM closes the loop on N_2. The HLC controls the demanded N_2 so as to achieve a fuel flow that is sufficient to result in the required power output. In a transient the accuracy only becomes critical if the fuel limit schedules are very close to the compressor surge, engine overtemperature or flameout limits. In the latter case, if the design of the fuel schedules provides considerable safety margins, then there is no need for great accuracy.

On the other hand, the actuator response has a large impact on the transient response of the engine. A sluggish actuator, for example, means that less fuel will be metered to the engine in a transient than is being demanded.

4.5 Fuel Schedules

The fuel control function of the ECM makes use of fuel limit schedules for startup, acceleration and deceleration of the engine. This section describes the design of the fuel schedules used by the ECM. It will be broken down into a discussion on the use of fuel schedules in gas turbine fuel controls, and a description of the design selected for the ECM.

a. Background on Fuel Schedules. The ideal method of controlling the flow of fuel to a gas turbine during an engine acceleration would be by means of closed loop control on both compressor flow stability margin (surge margin) and high pressure turbine inlet temperature. This approach would prevent compressor stall and avoid the high temperatures that occur by overfueling. Despite extensive studies and developments in these areas, no satisfactory means of sensing compressor stall is available and methods currently available for measuring high pressure turbine inlet temperature are extremely expensive.

Consequently, other engine parameters that can be measured easily and cheaply are used in designing the fuel control. These parameters are generally cast in the form of a fuel limit schedule. Most gas turbine fuel control units employ a simple droop governor to control fuel flow closing the loop on gas generator speed. The fuel flow is then limited by a suitable fuel limit schedule.

Much of the art of fuel control system design lies in choosing an acceleration fuel schedule so that engine accelerations always result in satisfactory trajectories of the operating point between steady state and compressor surge and/or engine temperature limits. The acceleration fuel schedule is also typically used to define the startup fuel flow for the engine. In the

startup region the fuel schedule is designed specifically to prevent overtemperatures. Deceleration fuel schedules are also frequently used. These define a minimum fuel flow limit below which flameout is likely to occur.

A fuel schedule is thus a method by which open loop control of surge, overtemperature, and flameout is provided. The usual method of defining the fuel schedule is to cast fuel flow in a non-dimensional form such as that shown in Figure 6. By using such a non-dimensional form, it is possible to determine the fuel flow limits necessary to maintain all transients within the safe operating envelope. There are many possible variations on the form of the fuel schedule parameter. Each has its own set of assumptions and requirements with regard to number and accuracy of engine sensors.

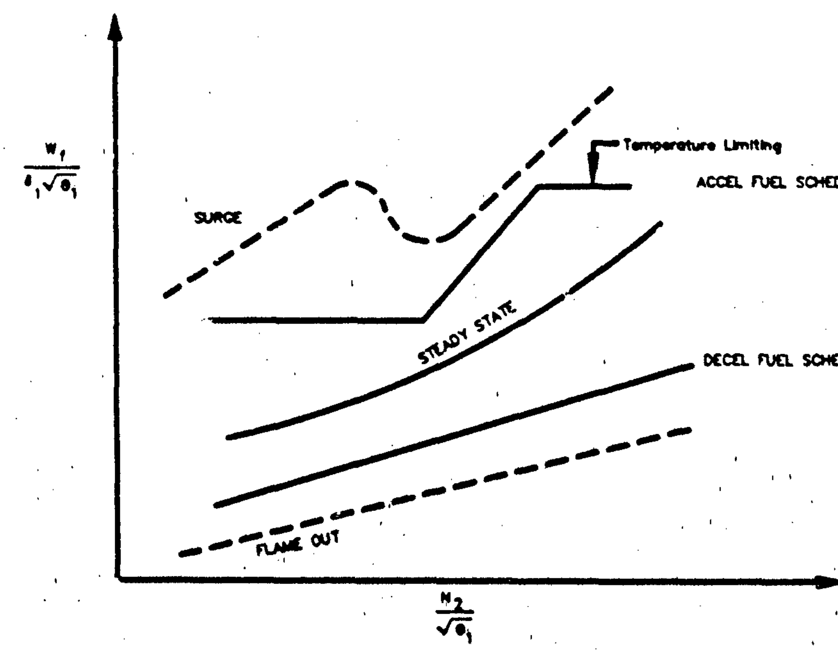


Figure 6: Typical Fuel Schedule

b. ECM Fuel Schedule Design. The acceleration and deceleration fuel limit schedules selected for the ECM are cast in the form $W_f/\sqrt{\theta_1} = f(N_2/\sqrt{\theta_1})$. This form of schedule only requires engine sensors providing a measure of N_2 and T_1.

The selection of this schedule was driven by two basic concerns. The first was a fundamental decision to tailor the fuel control algorithm to a marine propulsive application, specifically the DDH 280 warship. The second concern was to simplify the design by selecting a schedule that reduces the engine sensor requirements to a minimum and avoids the need for a complex control algorithm. Doing so improves the reliability of the design especially if it only makes use of reliable measurements.

The existing hydromechanical FT4 FCU uses a fuel schedule cast in the form $W_f/P_{3S} = f(N_2)$. This FCU was originally designed for an aircraft application where variations in ambient pressure are quite significant in terms of their impact on engine performance. However, the effect of sea level variations in ambient pressure are quite small. The need for including a pressure term in the fuel schedule parameter can therefore be eliminated in a marine application. Consequently the need for a pressure transducer can be eliminated thus simplifying the design and improving its reliability. The ECM fuel schedule parameter $W_f/\sqrt{\theta_1}$ was thus derived from the non-dimensional $W_f/(\delta_1\sqrt{\theta_1})$ by omitting δ_1.

Having established the desired form for the ECM fuel schedules, the transient response of the engine must be tuned by calibrating the schedules. As a minimum, the ECM fuel limit schedules must ensure that the engine operating point stays within the limits defined by the fuel schedule of the existing FT4 FCU. Engine transients (including hot re-accelerations) which respect the limits imposed by the existing FCU were assumed to be protected from compressor surge, engine overtemperature, and flameout.

It was determined through computer simulation that the transient response required in this application is much slower than that which is possible with the existing FCU which was designed for airborne applications. The simulation studies revealed that, over the operating range, an average gas generator acceleration rate of only $\dot{N}_2 = 200$ rpm/sec and an average deceleration rate of only $\dot{N}_2 = -300$ rpm/sec is sufficient. These transient response requirements must however be achievable under ambient temperatures varying between -60°F and 120°F.

The ECM fuel schedule was calibrated so that the above transient performance requirements were met. Note that the ECM fuel schedule is corrected for ambient temperature. That is the relationship between $W_f/\sqrt{\theta_1}$ and $N_2/\sqrt{\theta_1}$ is invariant with ambient temperature. Ambient temperature correction was required because of the desire to calibrate the fuel schedules to quite conservative settings. Attempting to do so without correcting for ambient temperature was found to compromise the engine performance at low ambient temperatures.

Calibration of the ECM fuel schedules was conducted using computer simulation studies. It was found that simple overfuel and underfuel ratio schedules could be used to quickly perform this task. The overfuel and underfuel ratio schedules were designed to vary linearly as a function of $N_2/\sqrt{\theta_1}$. They define the ratio between the engine's baseline steady state operating line and the acceleration and deceleration fuel schedules. The calibration procedure was found to be quite convenient and was therefore included as an automatic function of the ECM.

4.6 Droop Governor

The fuel control function of the ECM uses a simple N_2 droop governor. The droop governor controls the demanded fuel metering valve position by closing the loop on demanded N_2. This form of droop governor, also known as a proportional controller, is commonly used in gas turbine fuel controls. The existing FT4 FCU, for example, employs a droop governor.

The proportional gain, K_P, used in the droop governor can easily be tuned to limit the amount of overshoot and settling time in the N_2 response. In a digital application such as the ECM, however, this gain also depends on the controller update rate. The droop governor, by its nature, has a steady state error at all operating points. At any given ambient temperature the magnitude of the error depends on the proportional gain K_P.

The fact that there is a steady state error at all N_2 does not pose a problem so long as the input of N_{2I} to the ECM is capable of being varied between the minimum and maximum. This poses no problem because the N_{2I} input to the ECM will generally originate from the IMCS. Since the IMCS closes the loop on propeller shaft speed, the fact that there is a steady state error on N_2 is irrelevant. This is also the case when an operator is in direct control of N_{2I}. The value of N_{2I} can be thought of as being analogous to a throttle position which can be varied to vary the engine power output.

4.7 Engine Performance Simulation

The design of the ECM fuel control function discussed in the previous sections involved the extensive use of a computer simulation model. The design process was an iterative one where the computer model was initially used to define the engine performance requirements within the context of the DDH 280 application and to try out various candidate fuel control algorithms. Having arrived at a suitable overall design, the model was used to refine its various constituent components. This included the selection of update rates, setpoints and fuel limit schedules.

The computer model included dynamic models of the existing FT4 hydromechanical FCU, the ECM fuel control function, the FT4 gas turbine, a simple load device, and the DDH 280 ship. The model could be configured as an FT4 engine driving either the load device or the DDH 280 with fuel being controlled either by the ECM fuel control function or by the existing hydromechanical FCU. It was thus possible to compare the performance of the FT4 under the control of the proposed ECM against that of the existing FCU. The hydromechanical FCU was modelled as ideal; that is, it was modelled without the effects of any sensor error or any lags in the response of the fuel metering valve. With the ECM, these factors <u>were</u> taken into account.

In the ship mode, the pre-TRUMP DDH 280 propulsion machinery and pneumatic propulsion control system was modelled. In this mode the engine power is controlled by the pneumatic control system in response to ordered ship speed commands.

In the load device mode, the engine power is controlled directly by commanding an N_{2I}. The load device was used to initially test various fuel control concepts in a relatively simple manner by performing accelerations and deceleration of the engine in response to step changes in N_{2I}.

The FT4 gas turbine model was of course a key element of the computer simulation. It is capable of simulating the engine dynamics to a level that is quite adequate for fuel control design studies. The model makes use of an "auxiliary map" to define the behaviour of the engine both in steady state and in a transient. The auxiliary map contains data which was pre-computed from an engine component matching program. The dynamic model provides a measure of any of the engine gas path parameters taking into account the shaft dynamics. It assumes that the pressure dynamics of the gas path are very fast in comparison to the shaft dynamics. This is considered to be quite acceptable for fuel control studies of the FT4.

Simulation results for a zero to full ahead ship acceleration with fuel controlled according to the ECM fuel control function are shown in Figures 7 to 9. Figure 7 shows that even for a step change in ordered knots, the propulsion control system commands the engine power to increase quite slowly. The full transient response potential of the engine allowed by the ECM is not invoked. Note that the fuel limit schedule is only invoked momentarily at the beginning of the manoeuvre (see Figure 8).

Most of the transient occurs at fuel flows below the limit. In fact after about the first 10 seconds, the engine response could be considered to be quasi-steady state. The propulsion control system increases power at this slow rate to prevent the propeller shaft torque from rising beyond a specific limit. The

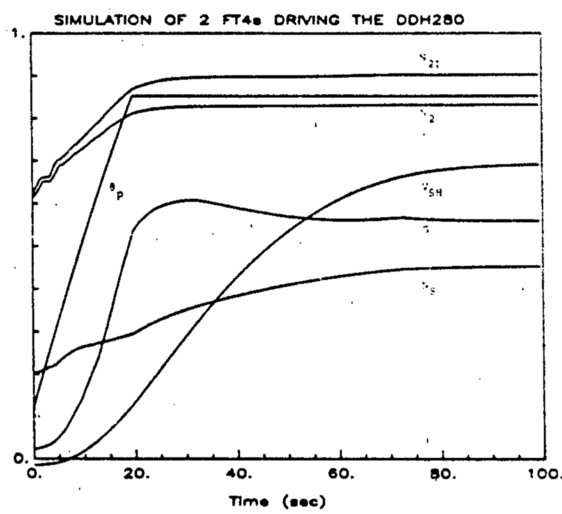


Figure 7: Ship and Engine Performance for Ship Acceleration with ECM

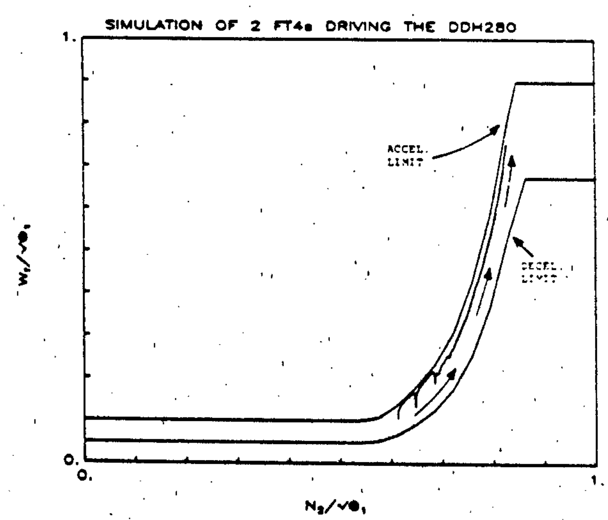


Figure 8: Fuel Schedule Transient for Ship Acceleration with ECM

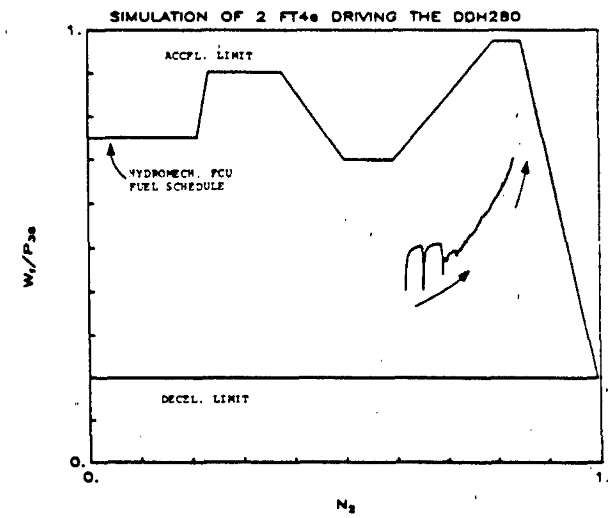


Figure 9: W_f/P_{3S} vs N_2 Transient for Ship Acceleration with ECM

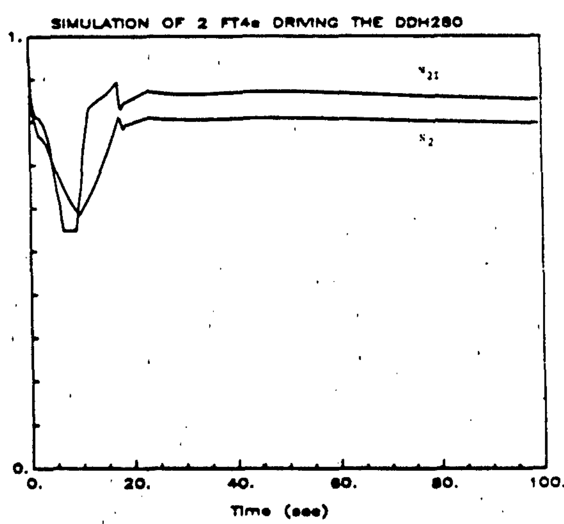


Figure 10: Engine Performance for Ship Crashback with ECM

transient performance of the ship (Figure 7) is thus limited by its drive train, not its engines.

Note that the trajectory of W_f/P_{3S} vs N_2 shown in Figure 9 indicates that there is considerable safety margin between the achieved response and that which would have been allowed by the fuel limit schedule of the existing FT4 hydromechanical FCU. When this simulation was repeated with fuel controlled by the hydromechanical FCU, almost identical engine and ship performance was obtained.

A crashback from full ahead to full astern is a more severe ma. .uvre with respect to engine performance because the propulsion control system demands very rapid deceleration and re-accelera'.ion of the engine. Simulation results for this manoeuvre wit fuel controlled according to the ECM fuel control function are shcwn in Figures 10 to 13. The gas generator undergoes a sudden deceleration and re-acceleration within the first 15 seconds of the manoeuvre (Figure 10). During this time the full transient response potential of the engine allowed by the ECM is invoked. This is illustrated in the fuel schedule transient shown in Figure 11.

At the same time however, the trajectory of W_f/P_{3S} vs N_2 shown in Figure 12 illustrates that there is still considerable safety margin between the achieved response and that which would have been allowed by the fuel limit schedule of the existing hydromechanical FCU. Clearly the fuel limit schedules used in the ECM are more restrictive than those used in the hydromechanical FCU.

When the crashback is repeated with the hydromechanical FCU in control, the full transient response potential of the engine allowed by the FCU is invoked (see Figure 14). This is considered to be an unnecessarily severe transient for the DDH 280 application.

This can be substantiated by witnessing that even though the hydromechanical FCU allows a quicker rate of engine response than the ECM, practically the same overall ship performance is achieved in each case (see Figure 13). The response of ship speed vs time is virtually identical in each case. However, note that a larger propeller shaft speed droop arises with the ECM in control. This occurs because the ECM doesn't allow the engine to re-apply power as quickly as the hydromechanical FCU.

If this amount of shaft speed droop is considered to be problematic then it is possible to raise the ECM fuel limit schedule to prevent it from occurring. However, this was not done because it was considered that the better approach would be to prevent the droop by modifying the ship's propulsion control

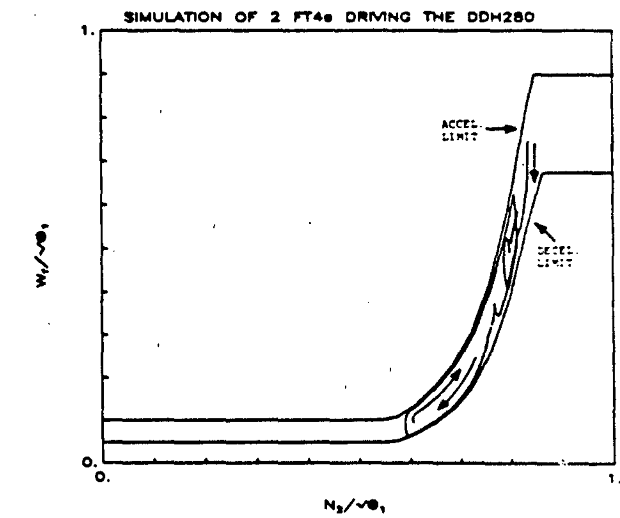


Figure 11: Fuel Schedule Transient for Ship Crashback with ECM

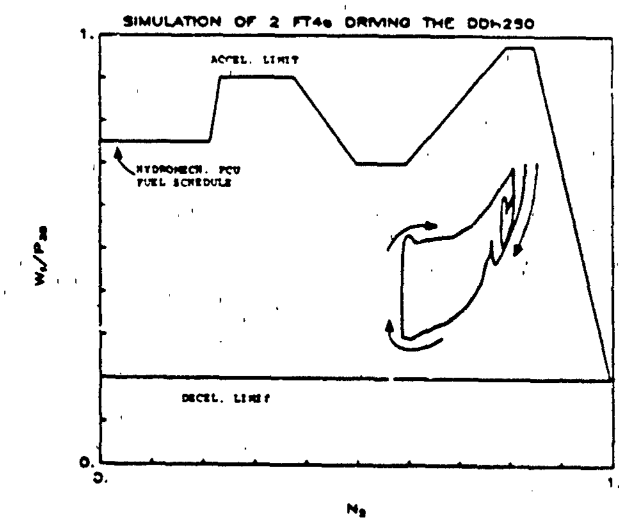


Figure 12: W_f/P_{3S} vs N_2 Transient for Ship Crashback with ECM

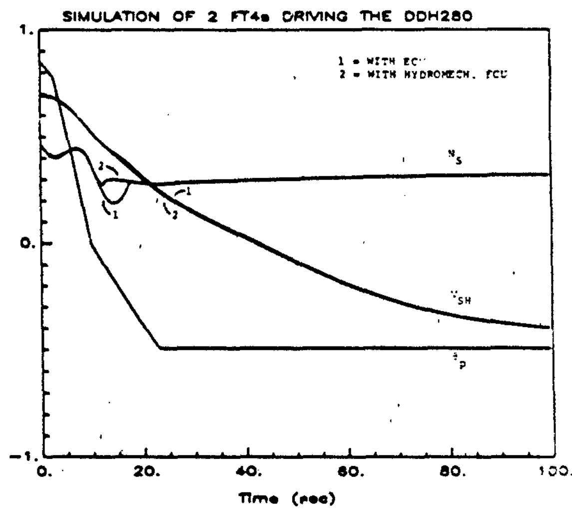


Figure 13: Ship Crashback Performance

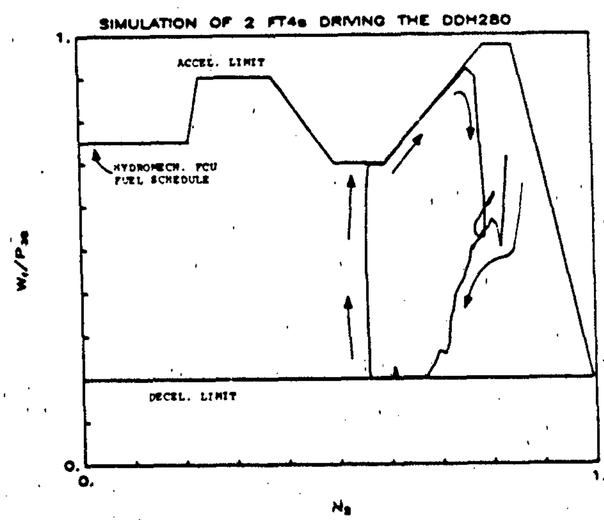


Figure 14: Fuel Schedule Transient for Ship Crashback with Hydromechanical FCU

system. For a crashback, the use of a fast idle power demand or better anticipation control, for example, can prevent the demanded power from being reduced to such a low level. The need for such a rapid re-acceleration would then be diminished and the control of propeller shaft speed droop simplified.

The need for such rapid power demand increases arise because of a mismanagement of power demand and load application by the pneumatic control system. The rapid engine response capable with the hydromechanical FCU compensates for this at the expense of invoking severe engine transients. The ECM is designed to prevent such severe transients with no significant changes in ship performance. Less severe transients are desirable since they can significantly prolong engine life.

5. ENGINE FUEL SYSTEM DESIGN

The existing FT4 fuel system design requires only a few modifications to incorporate the digital fuel control system design concept. Figure 15 shows a schematic of the existing fuel system in an engine running condition (taken from [5]).

The Hamilton Standard JFC 25-28 hydromechanical fuel control valve maintains a constant (temperature compensated) pressure differential across its metering valve by monitoring this pressure differential and returning excess pump discharge flow back to the fuel pump interstage chamber. Fuel flow is metered by positioning the precision plunger in the metering valve.

The existing system design incorporates a hydromechanical power turbine overspeed trip mechanism. In the event of a power turbine overspeed condition the N_3 gearbox driven mechanical speed sensor mechanism opens a set of switch contacts that are wired in series with one of the fuel shut off valve solenoid control circuits. The metered fuel flow is thereby cut off to the engine fuel manifolds.

The digital fuel control system design does not differ much from a conventional fuel control system design in terms of functionality. The major difference is in the manner in which the required engine performance parameters are monitored (sensed) and the manner in which the control logic is implemented.

Figure 16 shows a schematic for the digital fuel control system with a partial interface to the ECM. All of the major components are retained except for the hydromechanical fuel control unit, which is replaced with the fuel bypass and metering valve, and a fuel dump pilot control solenoid valve.

Whereas the fuel control algorithm is encoded mechanically within the hydromechanical fuel control valve, the algorithm is

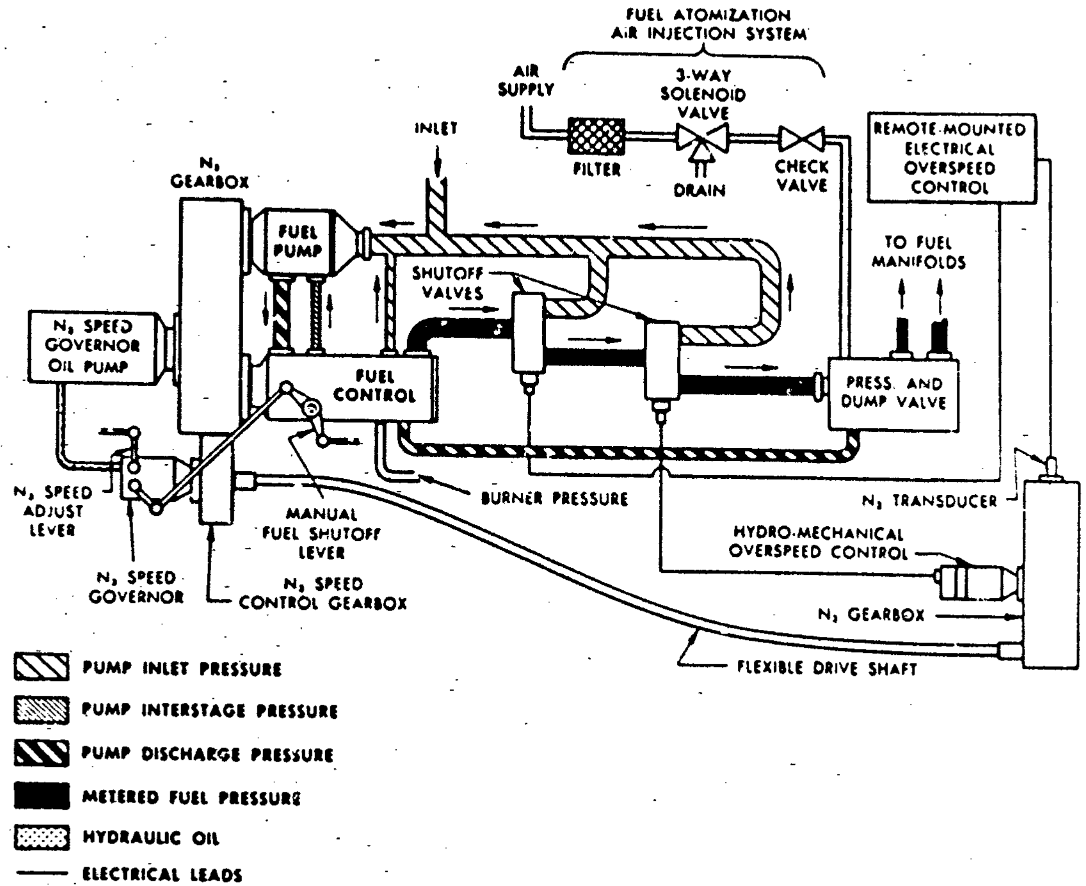


Figure 15: FT4 Gas Turbine Hydromechanical Fuel System Schemtic

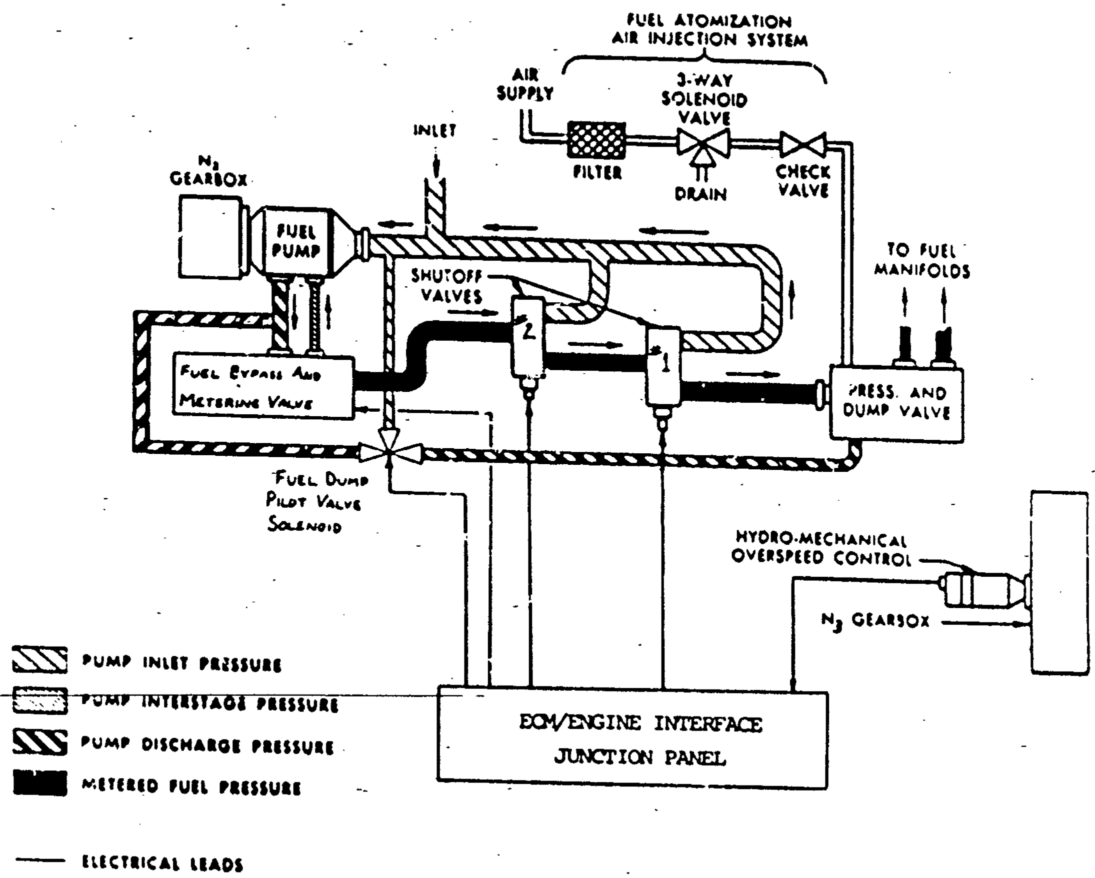


Figure 16: FT4 Gas Turbine Digital Fuel System Schematic

encoded in computer software for the digital fuel control system. The digital fuel control system senses engine performance electronically and sends an electrical control signal to the fuel metering valve actuator to actuate the precision metering valve plunger to control the fuel flow rate.

As with the hydromechanical fuel control valve there is a requirement that a mechanically controlled bypass valve return a portion of the fuel pump flow in order to maintain a constant (temperature compensated) pressure differential across the fuel metering section.

The fuel dump valve pilot signal control function of the hydromechanical fuel valve must be replaced with the fuel dump pilot solenoid as shown in Figure 16. This three-way solenoid valve supplies fuel pump discharge pressure to the dump valve pilot control line while the engine is running (solenoid energized) or provides fuel pump inlet pressure when the engine shuts down (solenoid de-energized).

The hydromechanical overspeed detection switch circuit is retained within the ECM design concept as a backup to the electronic overspeed protection circuit.

6. ECM LOGIC DESIGN

There are nine basic functions that must be performed by the engine control module (ECM):

1) Higher Level Controllers Interface Communication
2) Engine Interface Communication
3) Trip Command Processing
4) Battle Override and Bypass Commands Processing
5) Timer Operation
6) Engine Life Utilization Indice Functions
7) Engine Monitoring and Protection
8) Fuel Control
9) Engine Sequencing

6.1 Higher Level Controller Interface

Within the context of a digital integrated machinery control system (IMCS), the ECM as a unit controller must maintain a digital communication link with the higher level controller(s) (HLC) of the IMCS. This communication consists of the transmission of command signals to the ECM and the transmission of ECM feedback signals to the HLC.

Most of the HLC command signals are identified in the engine sequencing program command recognition chart (see Section 6.4,

Table 1). Other co..mands include the engine trip command, battle override command, and the bypass set/reset commands.

The operator has the capability of tripping the engine at any time by invoking the engine '. , command. This command is responded to whether or not th engine is actually running.

There are several bypasses that the operator may deploy which fall into three categories:

1) Start Permissive Bypasses
2) Power Cutback Bypasses
3) Trip Bypasses

Under normal circumstances there should be no reason to bypass any of these permissives. However, if for some reason it is necessary to start the engine or keep it running, bypass variables have been provided corresponding to each start permissive, power cutback, and engine trip. Only the power turbine overspeed trip cannot be bypassed since destruction of the engine and a threat to personnel safety is a foregone conclusion should it occur.

The operator may set and reset all bypasses individually. Using the battle override command the operator may set all of the power cutback and engine trip bypasses. (Note that the start permissives can not be set with the battle override).

There are several feedback signals that are either generated within the ECM or are simply transferred from the engine interface I/O that are available for communication with the HLC. There are 8 types of feedback signals:

1) engine performance parameters feedback
2) warning and information messages
3) status of engine trip bypasses, power cutback bypasses and start permissive bypasses
4) engine sequencing program (ESP) status
5) event counters
6) sequence and operational timers
7) trip reason (value = 0 if not in tripped condition)
8) start permissive failure reasons

Some of the data will serve as engine and ECM life utilization indices (LUI's) for the purpose of engine health monitoring.

6.2 Engine Monitoring and Protection

The logic specification for the ECM includes several engine monitoring and protection features. Table 2 provides a summary

Table 1   Engine Sequencing Program Command Recognition Chart

Engine Sequencing Program (ESP) Status \ Commands	Auto Start	Auto Stop	Auto Stop Abort	Starter Solenoid Select	Manual Ignition ON Select	Manual Stop	Motoring Cycle ON/OFF Select	Engine Wash ON/OFF Select	Reset	Test Mode ON/OFF Select	Manual Fuel ON Select	Air Assist ON/OFF Select	Fuel Valve #1 Test	Fuel Valve #2 Test	Low Power FSC	High Power FSC	Abort FSC
Tripped									✓								
Resetting																	
Reset									✓								
Shutdown									✓								
Ready to Motor							✓		✓								
Ready to Start	✓	✓		✓		✓	✓		✓	✓							
Shutdown Test Mode				✓	✓			✓		✓	✓	✓					
Auto Start Init																	
Auto Start Crank		✓															
Auto Start Lighting		✓															
Auto Start Accel		✓															
Auto Start Breakaway		✓															
Manual Start Init																	
Manual Start Crank					✓	✓											
Manual Start Lighting						✓											
Manual Start Accel						✓											
Manual Start Breakaway						✓											
Motoring Cycle Init																	
Motoring Cycle Crank							✓										
Motoring							✓	✓									
Motoring Wash							✓	✓									
Engine Running		✓				✓				✓							
Running Test Mode										✓			✓	✓	✓	✓	
Fuel Valve #1 Test																	
Fuel Valve #2 Test																	
FSC Stage 1,2,3,4,5,6																	✓
FSC Reset																	
Tripping																	
Auto Stop Rundown			✓														
Auto Stop Cooldown			✓														
(Tripping)																	

of all the engine monitoring and protection features. There are three basic types of engine monitoring and protection:

1) Warning
2) Power Cutback
3) Trip

If various engine conditions exist which are abnormal but are not immediately a threat to the safe operation of the engine, warning messages will be generated to notify the operator. The control of the engine will not be affected if such individual conditions arise.

If various engine conditions exist which are abnormal and may be a threat to the safe operation of the engine and which may be corrected by a reduction in engine power, a power cutback variable will be set which may reduce the speed demand from the higher level controller (provided the feature is not bypassed). These power cutback features are introduced to prevent an engine trip condition. Engine availability and life can be prolonged if unnecessary trips are avoided.

If various engine conditions exist which may be an immediate threat to the safe operation of the engine, an engine trip will be initiated provided that the individual trip feature is not bypassed. All the engine trip features shown in Table 2 may be bypassed by the operator except for the power turbine overspeed trip.

Table 2 also provides a summary of the prerequisites required for each engine monitoring and protection feature to be active. To avoid nuisance alarms (primarily when the engine is shutdown, e.g. low oil pressure) many of the features require that one of the following protection enable flags be turned on:

- ST ; Startup Protection Enable
- GG ; GG Running Protection Enable
- PT ; PT Running Protection Enable
- MO ; Motoring Protection Enable

These protection enable flags are internal ECM variables that are turned on and off by various engine sequencing function routines as appropriate.

6.3 Fuel Control

Under most normal operating conditions the gas generator speed demand (N_{2I}) from the HLC is transferred directly as the engine speed demand (N_{2D}), as long as it is within the bounds between the idle speed and the maximum allowable speed (N_{2DIDLE} and N_{2DMAX} respectively).

Table 2 Engine Monitoring and Protection Summary

	Engine Sensor Description	Type of Monitoring and/or Protection			Protection Enable Code
		Warning	Power Cutback	Trip	
1	GG Speed Signals	✓			GG
2	PT Speed Signals	✓			PT
3	PT Overspeed		✓	✓	
4	PTIT Average (Startup)			✓	ST
5	PTIT Average		✓	✓	
6	PTIT (Individual Sensors)	✓			
7	PTIT Flame Out			✓	GG
8	GG LO Level	✓			
9	PT LO Level	✓			
10	GG LO Pressure	✓		✓	GG, MO
11	PT LO Pressure	✓		✓	PT
12	GG LO Strainer ΔP	✓			
13	PT LO Strainer ΔP	✓			
14	GG LO Breather Pressure	✓		✓	
15	PT LO Breather Pressure	✓		✓	
16	GG LO Temperature	✓		✓	
17	PT LO Temperature	✓		✓	
18	Fuel Supply Pressure		✓	✓	ST, GG
19	Engine Vibration		✓	✓	GG
20	Fuel Meter Valve Position			✓	
21	Fuel Valve Current			✓	GG
22	Metal Chips	✓			
23	Enclosure Temperature	✓			
24	Igniter Puts	✓			

Protection Enable Codes: ST - Startup Protection Enable
GG - GG Running Protection Enable
PT - PT Running Protection Enable
MO - Motoring Protection Enable

There are circumstances, however, that necessitate modification of the speed demand input signal N_{2I} from the HLC to a cutback demand N_{2DCB}:

- power cutback initiated by an engine protection feature
- power cutback initiated by an automatic stop sequence

When a power cutback is initiated by one of the engine protection features the engine speed demand is reduced until either the adverse condition is removed, or the individual cutback feature is bypassed, at which time the speed demand is latched (i.e. held constant). Unless the battle override command is used the operator must reduce the HLC input speed demand to a value below the latched speed demand to recover control of the engine speed demand. If the battle override command is selected, all the cutback bypasses will be set thereby removing all the protection cutbacks and the cutback latch will be removed so that the engine speed demand automatically recovers back to the HLC speed input demand.

When a power cutback is initiated by the automatic stop sequence the engine speed demand will be reduced to idle and held at that speed (but not be latched) regardless of the condition of the battle override command until the stop sequence is completed.

6.4 Engine Sequencing

There are seven main categories of engine sequencing functions performed by the ECM:

1) Engine at Rest Functions
2) Auto Start Functions
3) Manual Start Functions
4) Motoring Cycle Functions
5) Engine Running Functions
6) Fuel Schedule Calibration Functions
7) Engine Shutdown Functions

Each of these main categories consist of several independent engine sequencing program (ESP) status functions. In total there are 36 ESP status functions.

The variable called "ESP status" is used to keep track of the status of the engine and the engine sequencing program status function that is to be executed. Only one ESP status function is executed each time an engine sequencing function is required to be executed.

There are six commands that are responded to independent of the ESP status functions:

1) Engine Trip Select
2) Battle Override
3) Set Bypass #(index)
4) Reset Bypass #(index)
5) Enclosure Fans ON/OFF Select
6) Engine Speed Demand

All the other commands are responded to as a function of the ESP status function being executed at any given time. Table 1 is the ESP command recognition chart. This table shows all the ESP status functions and indicates which commands are considered or responded to during each ESP status function execution. Note that some ESP status functions do not consider (i.e. ignore the condition of) some or any commands.

Each ESP status function has the capability of changing the ESP status variable depending on the condition of the various recognizable commands and/or various monitored engine parameters. Note that one command may trigger different controller responses depending on which ESP status function is being executed.

There are seven ESP status functions that are categorized as engine at rest functions:

1) Tripped (engine shutdown following a trip)
2) Resetting
3) Reset
4) Shutdown
5) Ready to Motor
6) Ready to Start
7) Shutdown Test Mode (manual maintenance mode)

In the "SHUTDOWN TEST MODE" the operator is permitted to manipulate the following control variables subject to certain limitations for the purpose of testing these components:

- starter solenoid valve
- fuel valve #1, fuel valve #1 startup, fuel valve #2, and fuel dump valve pilot
- ignition
- air assist
- engine wash valve

An operator should be qualified to operate these engine components from the "shutdown test mode". Although this ESP status function has been categorized as an "engine at rest" function it should be noted that it is still possible to start the engine. There are certain safeguards that are implemented to

prevent an operator from inadvertently attempting a dangerous sequence of events. For example, it is <u>not</u> possible for an operator to turn on the starter, turn on the fuel, turn off the starter and then turn on the ignition.

There are five ESP status functions that are categorized as auto start functions:

1) Auto Start Init (starter motor ON)
2) Auto Start Crank (waiting to achieve ignition speed)
3) Auto Start Lighting (waiting to verify ignition)
4) Auto Start Accelerate (waiting to achieve gas generator idle speed)
5) Auto Start Breakaway (waiting for power turbine shaft speed to increase)

Once an operator initiates the auto start sequence it will naturally progress through the above functions to achieve the ESP status of "ENGINE RUNNING"; however, the sequence is subject to various protection features which may cause an engine trip (fail to crank, fail to light, and fail to reach idle). An operator may abort the auto start sequence at any time by selecting the auto stop command.

The manual start sequence is very similar to the automatic start sequence, except that the operator decides when the fuel and ignition are turned on (simultaneously) after the ignition speed is reached. The automatic start sequence includes various sequence timing checks which may cause an engine trip whereas with the manual start sequence only warning messages may be generated for the same sequence checks (i.e. fail to crank, fail to light, fail to reach idle). An operator may abort the manual start sequence at any time by selecting the manual stop command.

There are four ESP status functions that are categorized as motoring functions:

1) Motoring Cycle Init (starter ON)
2) Motoring Cycle Crank (waiting to achieve motoring speed)
3) Motoring
4) Motoring Wash

The control system is capable of motoring the gas generator for the purpose of washing the engine and/or dry motoring the engine to purge it of fuel and moisture.

There are eleven ESP status functions that are categorized as engine running functions:

1) Engine Running
2) Running Test Mode
3) Fuel Valve #1 Test
4) Fuel Valve #2 Test
5-10) FSC (fuel schedule calibration) Stage 1 to Stage 6
11) FSC RESET

Upon completion of a manual start sequence or an automatic start sequence the ESP status will be "ENGINE RUNNING". While the engine is operated from idle to full power under normal operating modes the ESP status will remain "ENGINE RUNNING".

While the ESP status is "RUNNING TEST MODE" the following commands are recognized:

- Test Mode ON/OFF Select
- Fuel Valve #1 Test (independent fuel shut off)
- Fuel Valve #2 Test
- Low Power FSC (fuel schedule calibration)
- High Power FSC

There are four ESP status functions that are categorized as engine stopping functions:

1) Tripping (verification of engine shutdown following an engine trip)

2) Auto stop rundown (power cutback to idle following AUTO STOP command recognition)

3) Auto stop cooldown (running at idle for specific time period)

4) Stopping (verification of engine shutdown following auto stop cooldown or manual stop shutdown from idle)

By executing only the engine sequencing functions that are necessary, as determined by the ESP status variable, the ECM is able to perform this function very efficiently without wasting any execution time on unimportant tasks.

7. EMERGENCY ENGINE OPERATION

Notwithstanding the claims of high reliability and maintainability of the latest generation of digital control systems there is a respectable notion that in a marine environment (especially naval) there should be some means of operating the propulsion equipment independent of the electronic control system; that is, an emergency may warrant this mode of operation.

Although a gas turbine engine can not be operated in a truly manual mode (there is no hand crank for turning over the gas generator), there may be a requirement to effectively control the engine with basic (emergency) power supplies. What is proposed is that there be some means of switching the fundamental gas turbine engine control signals from the ECM control panel junction box with a set of emergency control signal actuators (switches etc.) on an emergency control panel. This emergency control panel is not to be confused with an LOP in the IMCS context which is an electronic local operating panel that coordinates with the ECM.

8. CONCLUSION

A digital marine gas turbine control concept has been developed for the P&WA FT4A-2 engine on the existing DDH 280 Class ships. The Canadian Navy originally selected this engine to prove and demonstrate the control concept for a number of reasons that made sense a few years ago [4]. However, in the foreseeable future, the Canadian Navy will also have GE LM2500 and Allison 570K gas turbines propelling its warships. These newer engines will require that both fuel flow and variable geometry be manipulated to control the engine. The present digital control concept can be extended quite easily to include the variable geometry control since the control system is being designed such that it can be adapted to other marine engines which the Canadian Navy will operate.

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DISCLAIMER

The views expressed in this paper are those of the authors and do not necessarily represent those of DND.

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NOMENCLATURE

CPF	-	Canadian Patrol Frigate
ECM	-	Engine Control Module
ESP	-	Engine Sequencing Program
FCU	-	Fuel Control Unit
GG	-	Gas Generator
HLC	-	Higher Level Controller
IMCS	-	Integrated Machinery Control System
PLA	-	Power Lever Angle
PT	-	Power Turbine
TRUMP	-	Tribal Class Update and Modernization Program
N_1	-	GG LP rotor speed
N_2	-	GG HP rotor speed
N_{2D}	-	Demanded N_2
N_{2I}	-	Demanded N_2 from HLC
N_{2DCB}	-	N_{2I} subject to power cutback
N_2	-	Rate of change of N_2
$N_2/\sqrt{\theta_1}$	-	Corrected N_2
P_{3S}	-	HP compressor delivery pressure (static)
W_f	-	Fuel flow
$W_f/\sqrt{\theta_1}$	-	Corrected fuel flow
T_1	-	GG inlet temperature
P_1	-	GG inlet pressure
T_a	-	Ambient temperature
T_{REF}	-	Reference temperature
P_{REF}	-	Reference pressure
SHP	-	Shaft Power
X_{FV}	-	Fuel Metering Valve Position
θ_P	-	Propeller pitch
N_S	-	Propeller shaft speed
G	-	Propeller torque
V_{SH}	-	Ship speed
θ_1	-	Temperature correction factor ($\theta_1 = T_1/T_{REF}$)
δ_1	-	Pressure correction factor ($\delta_1 = P_1/P_{REF}$)

FUTURE DIRECTION FOR ROYAL NAVY
MACHINERY CONTROL AND SURVEILLANCE SYSTEMS

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1. ABSTRACT

The use of digital technology within Machinery Control and Surveillance (MCAS) Systems has now been firmly adopted for all new RN warships under development and construction. The move towards digital control and surveillance has been gradual, being dictated by the need for cost effective systems that provide safe and reliable control in all action states. The greater flexibility of these digital software based systems has provided the means to increase the degree of automation and level of functional integration, ensuring the more effective use of manpower.

Greater integration and automation of platform functions can be achieved with current and emerging technologies, which could radically improve ship control centre manpower utilisation. The paper looks ahead to the next generation of RN warships discussing the requirement for greater platform integration and automation. It surveys some of issues which need to be resolved before this approach could confidently be adopted. These issues include, the concept of an Integrated Platform Management System, safety, hardware and software standards, extension of system automation, flexible Man Machine Interfaces (MMIs), improvements in system specification and changes in training policy.

2. INTRODUCTION

At a time when the latest RN warships are being accepted into service, it is appropriate to look ahead to the next generation warships to establish the broad requirements of the Platform Control and Surveillance Systems of these vessels. In doing so it is instructive to look at previous and current trends in Machinery Control and Surveillance (MACS) System design to establish the impact of these trends on future systems.

These trends and the limitations of current systems help to determine the likely direction of future system design and the resulting procurement and design issues. These issues need to be resolved to reduce programme risk and ensure that future systems can be specified with confidence.

3. CURRENT DESIGN TRENDS

The evolutionary change in design of warship control and surveillance systems over the last 30 years or so, appears to have followed broadly the same pattern in most NATO navies. The changes having been recorded in many of the past symposia papers.

Current RN new construction ships give a good indication of these trends and a pointer for the design of future systems. These trends can be seen by looking briefly at the design of the current major new construction vessels these being T23 Frigate (1), Single Role Minehunter (SRMH) (2) and Auxiliary Oiler Replenishment Vessel (AOR) (3).

These include the adoption of:

a. Distributed software based systems: which have to a large extent decentralised control to remote positions. Hardwired control and surveillance signals have been retained for vital functions (1) (2) (3).

b. Integrated Ship Control Centre: whereby all Damage Surveillance and Control (DSAC) and MCAS System functions have been integrated within a single large console to provide a more effective command centre. The Marine Engineering Officer (MEO) can from a single location have visibility of all functions (1).

c. Complex control systems: the integrated nature of the T23 CODLAG propulsion plant has required greater integration of the control system with a consequential increase in the automation and complexity of the MCAS system (1).

d. Interface with Ship Combat System: where operationally required, a link has been provided between the Combat System and the Platform control system to enable automatic modes of control (2).

e. Reduced manning: the T23 MCAS System has been designed to be operated by three watch-keepers in Defence State 3, which is a significant reduction from the T22 Frigate. The AOR has achieved manning levels more associated with the merchant fleet, with the Machinery Control Room (MCR) capable of being unmanned whilst cruising and manoeuvring at sea (3).

f. Larger Systems: a gradual increase in the size of MCAS Systems has been seen. The size of the AOR MCAS Systems (3) being the largest approximately 4000 control and monitoring input and output signals.

4. DEVELOPMENT CONSTRAINTS

The design of the current new construction ship MCAS Systems shows signficant improvements over previous designs. These designs have been dominated by the need to adopt well proven industrial technology to secure the high availability required of Naval Systems. Low risk technology has

been adopted to secure the maximum benefits in development cost and programme timescales. In addition to technological constraints, procurement policy has had a dramatic effect. Whole ship procurement and the pressure to reduce costs while undoubtedly reaping rewards in reducing ship procurement costs has held down the scope of the MCAS Systems to the minimum. The main losers being the operators who have not been provided with the many desirable facilities which would have improved operator efficiency.

As a consequence, within the wider context of the Ship and Platform System, interfaces with other systems or equipments have only been made on a strictly operational basis resulting in a largely piecemeal development of Platform Systems. In particular the opportunity to transfer data between systems even at a most basic level has not been taken. Likewise, in the main, automation has been applied where required by the complexity of the plant under control rather than from a desire to reduce operator workload.

The current design philosophy for RN warships also seriously limits the further development of more intelligent systems. In particular it would be difficult to provide:

a. Integrated management systems: which enables all platform data related to machinery operation and maintenance to be viewed, analysed and manipulated to enhance overall management.

b. Optimised ship control philosphy: to provide optimised and adaptive ship and machinery control performance for various operational and environmental conditions.

c. Centralised knowledge based systems: which provides enhanced decision aids for both operators and maintainers.

d. Further manpower reductions and/or improvements in efficiency: due to the design limitations of current man machine interfaces.

5. FURTHER DESIGN PRESSURES

In addition to current trends, other external pressures will motivate further change.

5.1 Demography

It has been suggested that the factor which will call for the greatest change in design philosophy is the so called demographic trough. Warnings have been given in the UK of the effects of demographic trends resulting from the fall in birth rate during the 1970s. It is noted that the UK is not unique in this respect West Germany, Italy, France, etc, all recording sizable reductions in school leavers by the year 2000. Further social changes and the expansion of the economy, with the consequential increased

demand for talented and qualified young people will put additional strain on the recruitment of Naval engineer officers, artificers and other ranks. Although developments in Eastern Europe may be a counterbalancing factor in the longer term.

The likely effects of demographic trends on recruitment and retention have been studied by the RN and measures taken to reduce the effects of the trough. Even with these measures it is likely that there will be increasing pressure on recruitment and retention. Therefore further measures might need to be considered to reduce ship manning levels.

Putting aside demography, in strictly economic terms it makes sense to reduce complements to reduce through life costs and ease the pressure on the defence expenditure. Further small reductions in Marine Engineering staff would be possible given the current state of technology but there would be a need to consider the wider consequences for ship operation. Radical reductions, whilst they may be feasible on paper, would require major changes in operating philosophies and manning structures. It would also be necessary to consider the impact of these measures right the whole naval service.

In conclusion it is considered that the trend towards further reductions in complement is set to continue over the longer term, with a continuation of previous trends and a gradual reduction in complement in each succeeding class. In the short term, radical reductions are considered unlikely.

5.2 Integrated Ship Machinery

The adoption of more integrated ship machinery systems could have a major influence on the design of control systems. This and the desire to provide optimal control philosphies to improve ship performance would lead naturally to future MCAS Systems requiring to be more complex, with greater levels of automation and integration.

5.3 Developments in Industrial Control Systems

Previous MCAS System designs have been dictated to some degree by the design philosphy and technology adopted by industry. Industry is already using or developing more Integrated Control systems in many forms, replacing hardwired control systems with those based on data transmission systems. Several hardware advances are taking place which will remove the engineering restrictions encountered in the past with integrated computer control and monitoring systems. The most notable being the current improvements in data transmission design, the increasing power of microprocessors and the rapid advances in the design of efficient Man Machine Interfaces. Thus within a short time, the technology to significantly enhance platform control and surveillance could be readily available at reasonable cost.

6. FUTURE DIRECTION

Based on the broad analysis of the design pressures and current trends it is possible to determine the likely direction of future system design development. This review will be restricted to so called near term systems, for ships with an in service date early in the next century.

6.1 Integrated Platform Management System (IPMS)

It is considered that further reductions in ME department manning and/or increase in efficiency and effectiveness can only be achieved by considering the platform on a "system basis" at the earliest stage in project development. System functionality should be improved by automating relevant tasks, further improving MMIs and ensuring that sophisticated Engineering Management aids are provided. All these aspects can be provided if sufficient consideration is given at the concept stage and they survive the inevitable pressures to reduce Ship Unit Production Costs.

To provide a focus for these developments it is helpful to consider these design issues under the collective title of the Integrated Platform Management System (IPMS). There is perhaps no definitive definition of IPMS, however it is generally accepted to refer to the integration of the Platform control and surveillance requirements into one system such that more efficient management of the Platform systems can be undertaken by marine engineering staff.

The real benefits of IPMS stem from the ability to transfer and manipulate data, if you like the application of information technology to the marine engineering function. Central to this, is the ability to automatically transfer data to other systems and the provision of intelligent displays or MMIs to enable storage and presentation of information in a user friendly manner. Of primary importance is the interface or integration of the platform control and surveillance and the Engineering Management System. The Engineering Management System would encompass a maintenance management system, an Integrated Condition Monitoring System (providing on line and manual data collection and handling facilities), OASIS (Onboard Automatic Data Processing Support in Ships and Submarines), etc.

The degree of integration is a debatable point and at its fullest could include all Platform Systems and including the Engineering Management System, see Figure 1. The full extent of the system would be dependent upon the analysis undertaken during ship concept and feasibility studies.

To implement such a system would require systems or equipment to be interconnected by some form of data transmission system or highway. Individual systems and equipments would be connected to the highway through standardised local data connection units. Operator access to the system being provided through flexible VDU based MMIs, see conceptual diagram Figure 2.

MCAS

Propulsion

Propulsor
Gearing
Clutches
Couplings
Locks
Shafts
Main Engines
etc......

Ancillaries

Fuel System
Lub Oil
Sea Water
etc......

Auxiliaries

Chilled Water
HVAC
Fresh Water
HP/LP Air
etc......

DSAC

Watertight Integrity
NBC Detection
Fire Detection
Ventilation Control
Flood Detection
Stability
Fire Fighting
etc......

ELECTRICAL POWER

Generation
Distribution
Conversion
Cathodic Protection
Degaussing
etc......

STEERING/STABILISATION

Steering Gear
Stabilisers
Trim/Ballast
etc......

OTHER MANAGEMENT SYSTEMS

Engineering Management Systems
OASIS
etc......

FIGURE 1
Sub-Systems which might be included in an Integrated Platform Management System

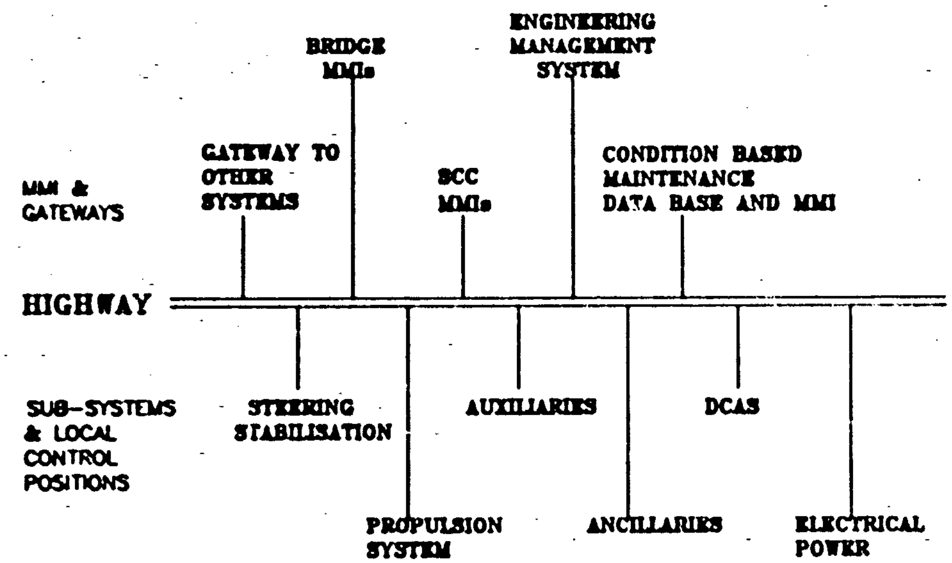

FIGURE 2
Conceptual Representation Of
Integrated Platform Management System

The move to an IPMS concept is seen as a logical evolution of current control and surveillance methodologies. The IPMS solution to platform control and surveillance although possibly increasing development and production costs will provide a more efficient and effective system. This will lead to the opportunity to at least reduce the man hours involved in the operation and maintenance of the Platform, and possibly reduce watch-keeping requirements still further resulting in through life cost savings.

6.2 Man Machine Interface

To date RN Surface Ship MCAS System information has been presented to the operator in a largely traditional manner. The use of discrete display devices and the general organisation of information on purpose built consoles has evolved from the Machinery Control Room (MCR) era to the current combined MCR and Damage Control Headquarters termed the Ship Control Centre (SSC).

The T23 has taken this a stage further by providing a large multi-function console and supervisor's console. Although much has been achieved with the T23 design it does not have the flexibility provided by a design based on multiple VDU's such as the Canadian SHINMACS (Ship Integrated Machinery Control System). Flexible MMIs are seen as one of the principle components of an IPMS design. It is therefore envisaged that future MMIs will rely more heavily on colour VDU's. This approach would provide a significant additional degree of flexibility enabling the MMI to be more effectively designed to match the skill of the operator and filter out unwanted information. It would provide a firmer basis for the introduction of IKBS techniques if deemed necessary and would be more in tune with the general trends toward this approach in the control industry.

7. ISSUES TO BE RESOLVED

The concept of the Integrated Platform Management System raises a number of issues which need to be resolved before an IPMS approach could be confidently specified for future ships. The main issues are discussed in the following paragraphs:

7.1 System Approach

Hitherto platform systems and equipments have largely been designed on a piecemeal basis. The advent of an IPMS concept will require a greater systems approach during specification, development, implementation and through life support than has previously been the case. The design of individual sub-systems and equipments encompassed by IPMS must also be subject to this systems approach. This requires the development of a wide ranging IPMS acquisition strategy to establish the policies and procedures to design, document and control all aspects of the IPMS design and implementation covering the total life of the project. It is possible that this will demand a change to current procurement policy and practices but the most significant change needs to be made at the specification stage.

The initial (perhaps obvious) step is to recognise that IPMS involves a significant change in complexity and in the number of interfaces, which demands a change in management approach. Further that IPMS is yet another system within the overall warship design and cannot be development in isolation from other systems. A top down systems approach needs to prevail in all aspects of ship and system design. This requires a more formal and therefore hopefully a more complete method of specification is undertaken.

A start has been made in this direction with the publication of Sea Systems Controllerate Publication (SSCP) 27 (Machinery Control and Surveillance System Specification Guide) which in addition to providing a framework for future specifications, recommends a top down approach and the use of structured analysis techniques. A separate paper provides a description of SSCP27 at this Symposium (4).

IPMS will require much more consideration to be given at the early specification stage to requirement elicitation. While considerably less complex than a modern Combat System, IPMS has many similarities when attempting to define system capabilities. The techniques and tools being developed mainly for Combat Systems could have been applied to the IPMS specification process.

The requirement specification of an IPMS needs to define in a complete and unambiguous manner the total functional requirements. Additionally it needs to define how well (in quantitative terms where possible) these functions are to be performed. Once specified the systems approach needs to be followed during design, development and implementation. This requires careful consideration of the procurement strategy and the division of responsibility within the total warship procurement. The IPMS Systems Manager should be given total responsibility for the system which would include integration responsibility for all platform electrical and mechanical machinery.

7.2 Safety

The safety of the plant and personnel needs to be given the highest priority. The increasing use of computers within Platform Control and Surveillance in general and specifically within IPMS raises a number of safety issues.

In the design of MCAS Systems it is current practice to separate primary controls, primary surveillance, secondary control and secondary surveillance, in order to ensure the appropriate levels of ship, plant and personnel safety. This being in line with the general principle of avoiding common mode failures. This is also in general agreement with the design principals exemplified by the registration requirements of the classification societies.

It was suggested earlier that IPMS could be assembled as one large system with control and surveillance signals passing along a common highway. As this is contrary to current design practice some rationalisation of these conflicting concepts is required. This issue has been raised at a time when the subject of safety critical software has been given additional impetus with the issue of the Health and Safety Executive Guidelines for Programmable Electronic Systems (5) and Interim Defence Standard 00-55 (6).

Ministry of Defence policy for the procurement and use of software in safety critical applications will be stated in Defence Standard 00-55. The main requirement of this standard is that all safety critical software is to be formally specified in a concise and unambiguous mathematical form. This standard is currently available as an Interim Defence Standard which has been subject to much debate and comment. However it provides a yardstick in an area where few standards have previously existed.

A companion Defence Standard 00-56 (7), which addresses the identification of safety critical components (not just Software) has also been issued as an interim standard. This details the methods of hazard analysis to be used to identify and assess the safety critical features of a system. It details the hazard analysis activities that should be undertaken at each life cycle phase to ensure rigid documentation of the risks and measures taken to reduce them. It is beyond the scope of this paper to cover the requirements of this standard and that of Def Stan 00-55. However it is clear that whether or not safety critical components are contained within an IPMS a Preliminary Hazard Analysis will be required. If this is undertaken, the analysis would be seen as the main vehicle for determining the safety of IPMS.

The presence of safety critical software within IPMS will invoke the rigorous standards of Def Stan 00-55 and would have a significant effect on system cost. At first sight a design strategy that eliminates the need for safety critical software may seem attractive. To achieve this could require reducing the level of automation, versatility or functionality of the system or alternatively requiring that additional supervisory safety systems (eg hardwired or non programmable systems) are provided. A balance must therefore be struck as a result of the Preliminary Hazard Analysis taking account of the cost, manning level and performance requirements of the system.

Undertaking a hazard analysis is not a small task, even at the preliminary stage. Although an IPMS would not in itself introduce many hazards, it has control over a number of potentially hazardous equipments. The preliminary hazard analysis must therefore be extended to include these equipments. This considerably increases the scope and complexity and hence the cost of the task. A balance must therefore be struck between the cost and scope of the analysis and the possible legal, safety and moral implications of not totally complying with the standard.

A retrospective examination of current software based MCAS System has revealed that a MCAS System provides a large number of safety critical features (ie is a feature of a system that eliminates an unacceptable hazard or reduces the risks to an acceptable level). This further underlines the need for a detailed hazard analysis during the feasibility stage to ensure adequate safety levels in the final design.

7.3 Software Standards

It has been a requirement for some time that all software in Platform Marine systems and equipments shall comply with Naval Engineering Standard (NES) 620 and that software development shall be carried out under approved quality assurance conditions.

It has been MOD policy from the 1 July 1987 that ADA is the single preferred high level language for Defence equipment. The design of current new construction warship MCAS systems were started prior to this date, so that the question of the use of ADA for MCAS systems has not yet been fully approached. Although issued as a policy statement applicable to all projects, it has tended in the intervening years to be left to individual project managers to determine the precise policy for their particular systems and equipments. This has arisen amongst other things because the ADA Programming Support Environment was slow to mature, the short term high cost overhead and the slow acceptance of ADA by industry, (perhaps as a result of the former). It has also been suggested that part of the problem has been the doubt on the real time system performance of ADA (8).

The principal benefit of ADA is stated to come over the longer term, where it is suggested that ADA will reduce maintenance costs of the system and reduce future system cost through reusable software modules. For IPMS and MCAS Systems, this raises the real possibility of re-useable software, as the functionality of these systems could be seen as being broadly constant with each succeeding system. However to be completely successful will require the creation of a software module library over which the MOD would retain the necessary intellectual property rights.

This leaves the use of ADA in future IPMS still in doubt. As the policy has been set there will be increasing pressure to ensure that projects conform. Future IPMS Specifications will at least need to include the requirement for bidders to quote for an ADA solution, as well as software to good commercial standards.

7.3 Data Transmission Standards

One of the major issues to be resolved for IPMS is that of data transmission and communications protocols for the Platform highway or Local Area Network (LAN). It is beyond the scope of this paper to discuss this subject adequately. It can be stated however that as far as possible these standards should be based on the International Standards Organisation Open System Interconnection (OSI) Basic Reference Model (9).

The standards to be adopted need to be selected from the relevant commercial and military standards taking into account the required real time performance requirements, need for high integrity and requirements for special functions. The LANs physical layer should be selected from current proven systems supported by industry.

Data transmission rate, bandwidth and system response times for IPMS will be very much lower than that required for Combat Systems. However savings could be made by adopting a whole ship approach to data transmission standards particularly where the ship operational requirements call for a sophisticated interface between IPMS and the Combat System.

7.5 Automation

RN Warships have achieved a high level of automation (that is the automation of sequences or procedures) and remote control (the operation of single action on demand). The T23 and SRMH have extended this, as described above and in previous symposium papers (1, 2). Remote control and later extensive automation has mainly been motivated by:

a. the need to control machinery from a central position within a gas tight citadel with unmanned machinery spaces.

b. the complexity and speed of response required for the control of modern ship machinery.

Many of the automation issues raised in previous Symposium papers particularly that of Marsh/Stafford (10) remain true today. Further automation other than that required by the introduction of more complex and integrated machinery systems will only be undertaken as a result of the cost savings realised through real reductions in manpower.

To a limited extent automation has been undertaken to reduce watch-keeping tasks, although the main thrust has been to provide more sophisticated remote surveillance systems. Indeed part of the on-going improvement of in service ship MCAS Systems has been the upgrading of surveillance equipment with modern digital surveillance systems (11).

It is evident that much more could be done to reduce operator workload. Simple, often manpower intensive tasks have not been automated because they do not fall within the criteria set out above. Whilst a fully automated system of the sort adopted in the commercial marine fleet would not be appropriate for a warship, much more could be done given the necessary impetus. A sensible balance needs to be struck between automated and manual systems, such that the benefits of automation are achieved whilst maintaining the flexibility of manual systems. This inevitably will require an examination of the cost effectiveness (in terms of through life costs), its viability in all ship operating states, safety, flexibility and operational requirement. A blanket approach could not be taken to automation. Each

system or sub-system needs to be examined to determine the optimum level of automation. A separate paper at this Symposium discusses the opportunity for automation of SCC functions (12).

7.6 Shore Based Reference Facility (SBRF)

With the advent of software based MCAS systems the requirement for prototyping and shore based Reference Facilities has become much greater. For the T23 MCAS systems and the SRMH Ship Positioning Control System (SPCS), it was agreed that independent assessment programmes should be undertaken (13, 14). Based on the success of these projects it is recommended that future MCAS systems development programmes should include the requirement for a Shore Based Reference Facility (SBRF).

The case for an SBRF becomes stronger when an IPMS approach is considered. The size and complexity of IPMS with the larger number of interfaces to other systems will require comprehensive testing facilities to assist in the development, commissioning, acceptance and through life support as part of an overall Integrated Logistic Support (ILS) strategy.

As with the T23 and SRMH Assessment projects the SBRF should be established using computer simulation at either plant or data transmission level. Various options are open for its location and procurement. As such a detailed investment appraisal of all the options needs to be carried out to determine the most cost effective solution for each ship project.

7.7 Human Factors

Flexible MMIs using colour displays are not new to the RN. They are used in many weapon systems and are being provided as part of the Decca Isis 250 surveillance system and the AOR MCAS system. However it is seen as a significant departure from previous design methods to require special attention during the specification and procurement phases of the future ship project.

A structured Human Factors programme should be undertaken starting at the concept stage and carried through each phase of procurement. This programme would need to be tailored to the specific requirements of the IPMS design but would be based largely on the structure provided in the various references on this subject (15, 16).

The design of the SCC and the IPMS MMIs would be heavily dependent on the agreed manning levels and assumed operator skills established by the Staff Target and Staff Requirement. Therefore it would be inappropriate to have fixed views on the design at this stage. However some broad principles can be set out at this stage, these being:

a. the SCC should be optimised for action state operation.

b. the benefits provided by large mimic panels in giving a quick overview of the total plant should not be lost. A mix technology approach, part mimic part VDU would give the ideal solution.

c. particular attention needs to be given to the design of the Supervisor's and MEO's position to ensure that they retain the necessary command overview.

7.8 Training

Another benefit of flexible MMIs is that they enable some form of onboard training to be conducted. It has become common for weapon systems to have training simulators built in to the MMI. This has not been possible in the Marine Engineering area where the need to provide vital control and surveillance functions (even when alongside) and the use of inflexible MMIs have precluded this form of training.

Onboard training could be provided during quiet periods using one of the unused MMIs, while vital control and surveillance functions are provided by one or other of the consoles. This training would be part of continuation training, reinforcing that provided during pre-joining training (PJT). It has been suggested that there is a greater need for this type of training where more automated systems are used. The concern is that with a more automated IPMS the operator will become too heavily reliant on the MMI and lose the conceptual model of the ship system currently required of more manual control methods, this knowledge primarily being required during reversionary modes of system operation. Therefore it is important that training reinforces System knowledge of the ME equipment. The types of training that need to be covered are:

a. Training on the Ship Marine Engineering Systems.

b. Procedural training on machinery breakdown, including reversionary control.

Systems training would be the easiest to provide being merely a form of Computer Based Training (CBT). It may be possible to provide onboard the same couseware provided by the shore CBT system. If onboard training were restricted to this type of training it would probably be more cost effective to provide it on a separate PC outside the SCC. This could be used for a wide range of CBT packages applicable to training throughout the ship. Procedural training could only effectively be covered on the SCC Console and would require a means to effectively isolate the console from the ship systems during training. This raises both personnel and system safety implications which need to be thoroughly examined before it could be implemented. It must be emphasised that an onboard simulator would not replace the need for shore based facilities. This brings into question the cost effectiveness of sophisticated onboard training. It is clear that a sensible balance needs to be struck. At a minimum on board CBT could be provided very cost effectively on a separate PC.

8. CONCLUSION

Development of an IPMS concept for next generation surface ships is seen to be following the previous and current trends towards more effective use of manpower for Platform Control and Surveillance. Progress towards this concept should be gradual in order to reduce programme risk to a minimum. Where possible advantage should be taken of using proven military and industrial experience and standards, to provide cost effective, safe and reliable systems.

The form of IPMS has yet to be decided, it being a function of many factors including target manning levels, safety considerations, acquisition cost and through life costs. The design of an IPMS cannot be isolated from that of the ship and other systems. Therefore a whole ship system approach needs to be taken throughout the procurement cycle.

Although the system can be designed within the constraints of current and emerging technology it is the management of, the system specification, development and integration that presents the greatest risk and challenge. To meet this challenge will require the adoption of more formal specification and design techniques by both the MOD and industry, and the recognition of the special nature of this approach.

The views expressed in this paper are those of the author and do not necessarily represent the official views of the Ministry of Defence.

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A NEW APPROACH FOR ADAPTIVE RUDDER ROLL STABILIZATION CONTROL

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1. ABSTRACT

In this paper a newly developed model structure for describing the rudder-yaw and -roll dynamics is used for the adaptive controller design. The identification and adaptive control methods used are recursive prediction error (RPE) techniques, which directly identify linear or nonlinear rudder-yaw and -roll dynamics in a state-space model. The parameters and states of the multivariable rudder-yaw and -roll models (linear or nonlinear) are estimated simultaneously. A LQG optimal control strategy has been accordingly adopted with a combination of RPE identification. Simulations with free sailing model test data have shown excellent adaptive control responses in both course accuracy and roll reduction.

2. INTRODUCTION

A number of researchers have concentrated on rudder roll stabilization since the early 1970's, e.g. Cowley and Lambert [10], Carley [8], Lloyd [15] and Amerongen et.al. [1,2,4]. Autopilot control for rudder roll stabilization has also been researched and developed in the 1980's, e.g. Kallstrom [11], Amerongen et.al. [3,4], Katebi, Wong and Grimble [12] and Blanke et.al. [7]. Thus far, only simplified linear models have been used for control due to difficulties encountered with direct identification of a rudder-yaw and -roll model, inherent coupling effects and nonlinearities involved. For an autopilot, a simplified structure with a first order model of rudder-yaw rate and a second order model of rudder-

roll was suggested by Amerongen and Klugt [4]. A similar one was proposed by Katebi et.al. [12]. A rudder-roll damping system based on a state-space model with three rudders, has recently been introduced by Blanke et.al [7]. Linear rudder-yaw and -roll models were also introduced by Christensen and Blanke [9], and Zhou [20]. Investigations of nonlinear steering models with roll motion were made by Lloyd [15], Son and Nomoto [16], Kallstrom and Ottoson [11], and Zhou et.al. [23].

The conventional roll stabilization systems commonly use fins as the actuator. Thus, two separate control systems are used for steering and roll stabilization. Such a roll stabilization system generally does not work well due to the interaction by the fins not only on roll but also on heading. The philosophy behind rudder roll stabilization is that the rudder can be used as the only actuator to control both steering and roll reduction. This has the advantage of simplifying not only control but also hydraulic systems and fuel savings.

In order to control the two outputs at heading and roll with only one input from the rudder, two control strategies might be considered. The first strategy is to properly decouple the two control loops and then use the single input single output (SISO) method to control the separated loops. This has been possible by using low frequency rudder angles to control heading and high frequency rudder angles to control roll reduction. A drawback of this method, however, is that the coupling effects from roll, yaw and sway are disregarded despite the fact that they are significant to the dynamics, thus rendering this model inaccurate. This has been investigated by the authors in a previous paper [23]. The second strategy is a direct method based on a multivariable model, with a state-space model directly identified and then an optimal LQG control being adopted. The key point of the second method is that the identification algorithm should be capable of identifying a large dimension state-space model (4th order or more) with guaranteed convergence and unbiased estimation properties. In this paper the second method will be successfully applied using the RPE technique.

3. SHIP DYNAMICS

The linear ship-steering model with decoupled roll motion is well known. Once the roll motion from ship hydrodynamic theory is considered, the linearized steering model may have the form (Zhou [20]):

$$
\begin{bmatrix} (m - Y_{\dot{v}}) & (mx_G - Y_{\dot{r}}) & (-mz_G - Y_{\dot{p}}) \\ (mx_G - N_{\dot{v}}) & (I_z - N_{\dot{r}}) & 0 \\ (-mz_G - K_{\dot{v}}) & 0 & (I_x - K_{\dot{p}}) \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{p} \end{bmatrix}
= \begin{bmatrix} Y_v & (Y_r - m) & Y_p \\ N_v & (N_r - mx_G) & N_p \\ K_v & (K_r + mz_G) & K_p \end{bmatrix} \begin{bmatrix} v \\ r \\ p \end{bmatrix} + \begin{bmatrix} Y_\phi \\ N_\phi \\ (K_\phi - WGM) \end{bmatrix} \phi + \begin{bmatrix} Y_\delta \\ N_\delta \\ K_\delta \end{bmatrix} \delta \tag{2.1}
$$

Table 1. List of symbols in ship steering equations

m	mass of the ship
v	sway velocity
r	yaw rate (rate of turn)
p	roll rate
ϕ	roll angle
δ	rudder angle
x_G, z_G	Coordinates for the centre of mass related to x and z direction respectively.
I_x, I_z	moments of inertia about the x and z axes respectively.
Y_i, N_i, K_i	($i=v,r,p,\phi,\delta$) hydrodynamic coefficients (forces Y_i and moments N_i, K_i) related to y, z and x respectively.
W	mass of water entrained by the ship
MG	metacentric height

Transformation of (2.1) to a state variable representation can also be written as:

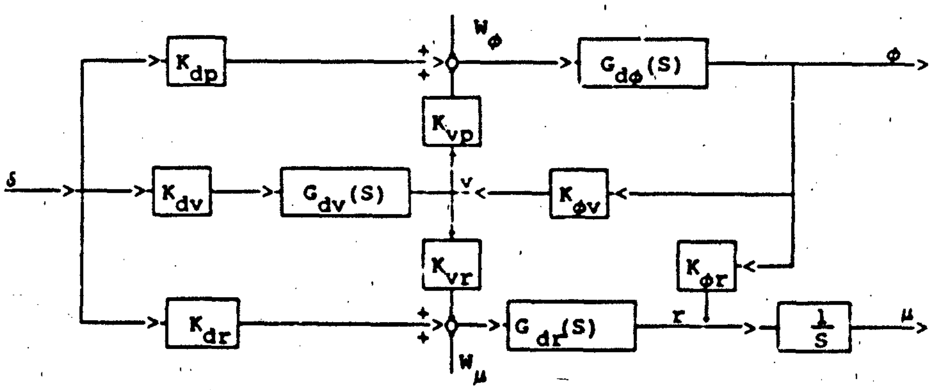
$$
\begin{bmatrix} \dot{\phi} \\ \dot{p} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \phi \\ p \\ v \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} \delta \tag{2.2}
$$

Thus the steering dynamics are represented by a 4th-order state-space model. It is well known that the parameters a_{33}, a_{34}, a_{43}, a_{44}, b_3, and b_4 represent the main part of the linear steering

dynamic model, as decoupled from the roll motion. In this case, a second order transfer function can be derived to represent the relationships of rudder-yaw rate and rudder-sway velocity, for example, Blanke [9]. Generally, rudder-roll angle can be described by a second order transfer function, which is given by parameters a_{21}, a_{22}, and b_2. The parameters a_{23} and a_{24} together with a_{21}, a_{22} then represent the relationship of sway-roll and yaw-roll through the second order function respectively. The parameters a_{31}, a_{32}, and a_{41}, a_{42} function as the coupling effects of roll motion to sway and yaw respectively.

A recent study of the rudder-yaw and -roll dynamic model shows that the coupling effects of a_{24}, a_{32}, and a_{42} in the linear model (2.2) are insignificant [23], and a nonlinear term n(t) given by Eq. 2.3 has also been found significant when added to the linear model. The structure of the linear rudder-yaw and -roll model is shown in Figure 1.

$$n(t) = \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \end{bmatrix} |\phi|\phi \tag{2.3}$$



where $G_{d\phi}(S)$, $G_{dv}(S)$ and $G_{dr}(S)$ are transfer functions between rudder and roll, rudder and sway, and rudder and yaw respectively, as is usual with all with second order models.

Figure 1. A linear model structure of rudder-yaw and -roll

Function $G_{dr}(S)$ may be of the first order model when the ship is large enough and rudder-yaw motions are in a low frequency range. The parameters K_{ij} are the gain coefficients of coupling effects between variables.

The disturbances acting on a ship are mainly due to wind, waves and current. Generally wind can be modeled as a stochastic signal with a non-zero mean. The non-zero mean value causes a constant roll angle as well as a constant heading error. The constant roll can be removed from the measured roll angle by an appropriate filter because it cannot be compensated by a rudder-roll stabilization system. The stochastic variations can then be treated as a white-noise signal. When current is assumed to be steady and uniform it can be ignored in the roll stabilization system. Variations in roll angle are mainly caused by waves. Several methods for approximating wave action can be found in the literature [4]. One possibility is to use a second order filter driven by white noise, as below:

$$H(s) = \frac{K_a s}{s^2 + 2\tau w_x s + w_x^2} \tag{2.4}$$

4. THE RPE ALGORITHM

The linear recursive prediction error (RPE) algorithm in a state-space model was initially introduced by Ljung [13] and Ljung and Soderstrom [14]. Extensions to the nonlinear state-space models were made by Zhou [18,20] and Zhou and Blanke [19]. The structure of the RPE method in a state-space model mainly consists of three parts:

1) parameter estimator (with Gauss-Newton search direction)
2) state estimator (linear or nonlinear)
3) gradient calculator

During one sampling interval, the parameter and state estimators are executed in parallel, mutually exchanged, and the gradient is calculated. The structure of the RPE method is shown in Figure 2.

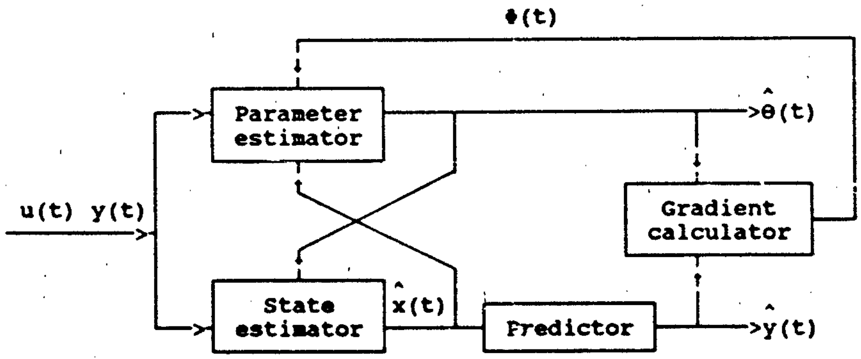


Figure 2. Structure of the RPE method

A unified form with Gauss-Newton direction is used for the parameter estimator. A linear filter and an approximate second order nonlinear filter combined with Ljung's innovations model (in which the Kalman gain matrix is estimated) are employed as the state estimators in linear and nonlinear cases respectively. Both discrete and continuous-discrete versions of the linear and nonlinear RPE methods are derived. For detailed linear and nonlinear RPE algorithms, refer to Ljung and Soderstrom [14], Zhou [19,22]. In this paper the continuous-discrete versions of the RPE method are employed because the physical terms can be preserved. This allows a dramatic reduction in the estimated number of parameters by ignoring those parameters actually known in the model and estimating those unknown.

5. CONTROLLER DESIGN

In design of the autopilot as well as rudder-roll stabilization systems, technical requirements are, that the rudder angle be limited by the mechanical constraints of the steering machine (in general the rudder angle is always less than 35 degrees), that the maximum rudder speed be determined by the maximum capacity of the hydraulic pump and that the steering mechanism control accuracy. Because rudder roll stabilization requires fast and large rudder motions, the maximum rudder speed must not be too low. When the rudder speed is too low, the steering machine causes an observable phase lag which changes the required control signal and thus completely deteriorates the performance of the system. Thus, the controller should be designed to ensure that the rate of change of the controller output is not larger than the maximum speed of the rudder.

5.1 The state-space model of the system

From Equation 2.1 and 2.2, the linearized system of the rudder roll stabilization can be described by the following state-space model:

$$\dot{x}(t) = Ax(t) + Bu(t) + Dw(t)$$

$$y(t) = Cx(t)$$

$$x^T(t) = [\phi,\ \dot{\phi},\ v,\ r],\quad u(t) = \delta(t),\quad w^T(t) = [w_\phi,\ w_\mu] \tag{4.1}$$

where x is state vector, u input signal from rudder and w white noises from roll and yaw. The process dynamic matrix A, input vector B and noise matrix D are in the forms:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & 0 \\ a_{31} & 0 & a_{33} & a_{34} \\ a_{41} & 0 & a_{43} & a_{44} \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} \qquad D = \begin{bmatrix} 0 & 0 \\ d_{21} & 0 \\ 0 & 0 \\ 0 & d_{42} \end{bmatrix} \tag{4.2}$$

The measurement matrix C is assumed as an identity matrix.

5.2 The adaptive RPE-LQG controller

The rudder roll stabilization system described by Equation 4.1 will be realized by an adaptive autopilot. The principle behind the RPE-LQG adaptive controller is that the parameters and the state of Equation 4.1 are estimated by the RPE identification method which then allows optimal linear quadratic Gaussion (LQG) controller to be employed to minimize all of the states x (the feedback in the system). The adaptive RPE-LQG controller is shown in Figure 3.

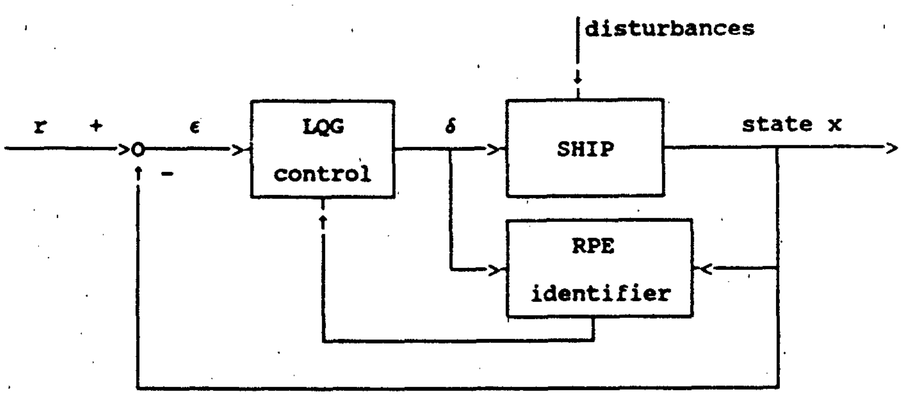


Figure 3. Adaptive RPE-LQG control

In general some convergent difficulties may occur in identification when all parameters in a large dimension state-space model are estimated simultaneously. In order to avoid this difficulty and thus reduce the number of estimated parameters in the continuous time state-space model (due to those physically known terms to be zeros), we choose the continuous-discrete version of the RPE algorithm.

For linear identification, a linear continuous-discrete version of the RPE algorithm is used in the form as follows:

$$\frac{d}{dt}\hat{x}(t|t_i^+,\theta) = A(\theta)\hat{x}(t|t_i^+,\theta) + B(\theta)u(t|t_i) \tag{4.3a}$$

$$\frac{d}{dt}W(t|t_i^+) = A(\theta)W(t|t_i^+) + M(t_i) \tag{4.3b}$$

$$\phi(t_{i+1}) = W^T(t_{i+1}^-)C^T(\theta) + D^T(t_i) \tag{4.3c}$$

$$\epsilon(t_{i+1}) = y(t_{i+1}) - C(\theta)\hat{x}(t_{i-1}^-,\theta) \tag{4.3d}$$

$$\hat{\Gamma}(t_i) = \hat{\Gamma}(t_{i-1}) + \alpha(t_i)[\epsilon(t_i)\epsilon^T(t_i) - \hat{\Gamma}(t_{i-1})] \tag{4.3e}$$

$$R(t_i) = R(t_{i-1}) + \alpha(t_i)[\phi(t_i)\hat{\Gamma}^{-1}(t_i)\phi^T(t_i) - R(t_{i-1})] \tag{4.3f}$$

$$\hat{\theta}(t_i) = \hat{\theta}(t_{i-1}) + \alpha(t_i)R^{-1}(t_i)\Phi(t_i)\hat{\Gamma}^{-1}(t_i)\epsilon(t_i) \tag{4.3g}$$

$$\hat{x}(t_{i+1}^{+},\theta) = \hat{x}(t_{i+1}^{-},\theta) + X(\theta)\epsilon(t_{i+1}) \tag{4.3h}$$

$$W(t_{i+1}^{+}) = [I - K(\theta)C(\theta)]W(t_{i+1}^{-}) + N(t_{i+1}) - K(\theta)D(t_i) \tag{4.3i}$$

where between two samples the prior estimate of the state $x(t_{i+1}^{-})$ and the sensitivity matrix $W(t_{i+1}^{-})$ are obtained after the propagation of (Equation 4.3a,b), and the posterior $x(t_{i+1}^{+})$ and $W(t_{i+1}^{+})$ by the measurement update (Equation 4.3h,i).

The matrices $M(t_i)$ is denoted as:

$$M(t_i) = \frac{\delta}{\delta\theta}\left(A(\theta)\hat{x} + B(\theta)u\right)\Big|_{\theta=\hat{\theta}(t_i)} \tag{4.4}$$

This is the partial derivative of the parameter matrices. The matrix $N(t_{i+1})$ is denoted as:

$$N(t_i) = \frac{\delta}{\delta\theta} K(\theta)\epsilon\Big|_{\theta=\hat{\theta}(t_i)} \tag{4.5}$$

This is the partial derivative of the Kalman gain matrix $K(\theta)$.

In the RPE algorithm, the state estimator is found in Equation 4.3a,h, the parameter estimator is found in Equation 4.3d-g, and the gradient calculator is found in Equation 4.3b,c,i.

In the adaptive LQG control a quadratic criterion can be defined:

$$J = \lim_{\tau\to\infty} \frac{1}{\tau}\int_0^\tau \left(y^T(t)Qy(t) + u^T(t)Ru(t)\right)dt \tag{4.6}$$

and the optimal controller can be calculated:

$$u(t) = -K\hat{x}(t) \tag{4.7}$$

where the gain matrix K is calculated by solving the Riccati equation:

$$K = R^{-1}B^TP \tag{4.8}$$

$$- \dot{P} = A^T P + PA + C^T QC - PBK \qquad (4.9)$$

During the sampling interval, the parameters and the states of the system are estimated by the RPE algorithm, and the adaptive LQG controller is then realized by using the strategy of Equation 4.7.

6. SIMULATION

The RPE-LQG adaptive controller shown in section 4 was tested with simulations. A simulation package was used to imitate the ship dynamics shown in Figure 3. The RPE identifier (linear or nonlinear) and an LQG optimal controller were employed simultaneously in every sample interval. The tests of linear and nonlinear RPE-LQG controls which are related to the linear model (Equation 2.2) and the model of Equation 2.2, adding the nonlinear term (Equation 2.3) were carried out. The linear and nonlinear RPE identification algorithms were used in both cases to build the on-line dynamic models. In the nonlinear case only the linear part (Equation 2.2) of the nonlinear model (Equation 2.2 plus Equation 2.3) was used to calculate the LQG control, due to the shortage of a nonlinear controller available so far.

In the test of the RPE-LQG adaptive control a set of free sailing ship model test data was employed to build a stable dynamic model which was assumed to describe the initial dynamics of the ship to be controlled. This was done by using the linear and nonlinear RPE identification algorithms in both cases. When a stable dynamic model was achieved, the RPE-LQG adaptive controller was then shifted and applied. Figure 4 shows the results of 12 identified parameters in the linear model (Equation 2.2). The first 160 samples indicate the results of initial identification for a stable dynamic model. The remaining 160 samples indicate the results of identified parameters when the RPE-LQG control was applied. The ship's responses to simulated waves are the solid lines shown in Figures 7 and 8. A maximum roll angle of approximately 30 degrees was simulated because no roll stabilization was applied. Figures 7 and 8 compare the ship's responses with roll stabilization (cross lines) and without roll stabilization (solid lines) using linear and nonlinear identification techniques respectively. Results clearly demonstrate the promising capability of roll reductions (about 75%) and resulting small course deviations in both linear and nonlinear algorithms. The control actions of rudder angles are shown in Figures 5 and 6 for both linear and nonlinear cases respectively. The linear RPE-LQG controller indicates slightly better results (Figures 5 and 7) compared with the nonlinear one in Figures 6 and

8. This is possibly caused by a well matched model (the same model used in both the RPE identification and the LQG control) in the linear case and a mismatched model (a nonlinear model in the RPE identification and a linear model in LQG control) in the nonlinear case.

7. CONCLUSIONS

This paper has presented a newly developed multivariable adaptive controller used for roll stabilization systems. This is carried out by using the RPE identification techniques. Results obtained by simulations show a promising capability of RPE-LQG adaptive control when applied to such a practical multivariable system. A key feature of the RPE-LQG control is that an accurate dynamic model of a multivariable system can be obtained by using the RPE technique, which is generally difficult with other methods. This causes more accurate LQG control over such an identification model. Large roll reduction and rather small course deviation are also a salient feature of this method. A study of the RPE-LQG roll stabilization implemented on a real ship will be a future goal for this project.

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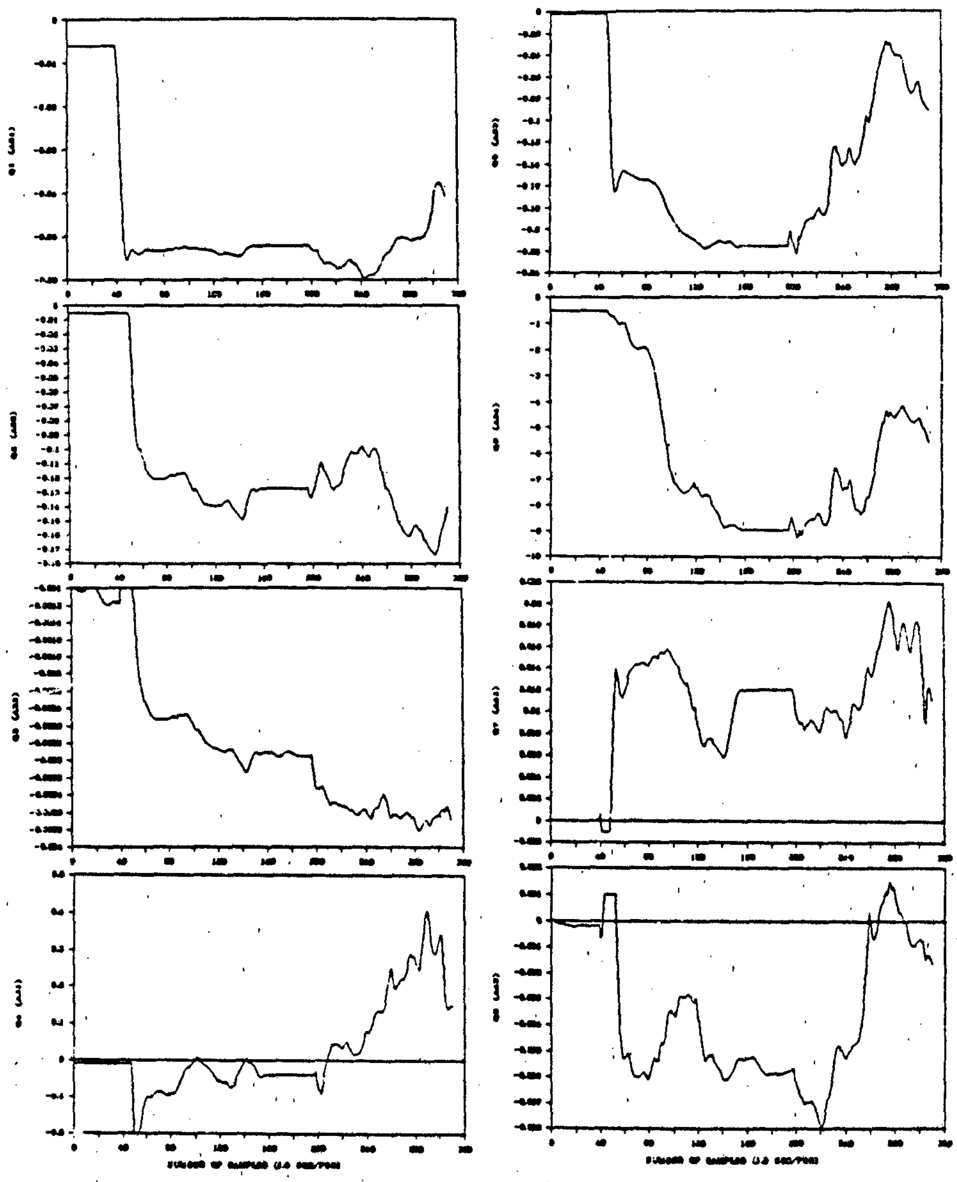

Figure 4: Identified parameters in model (2.2)

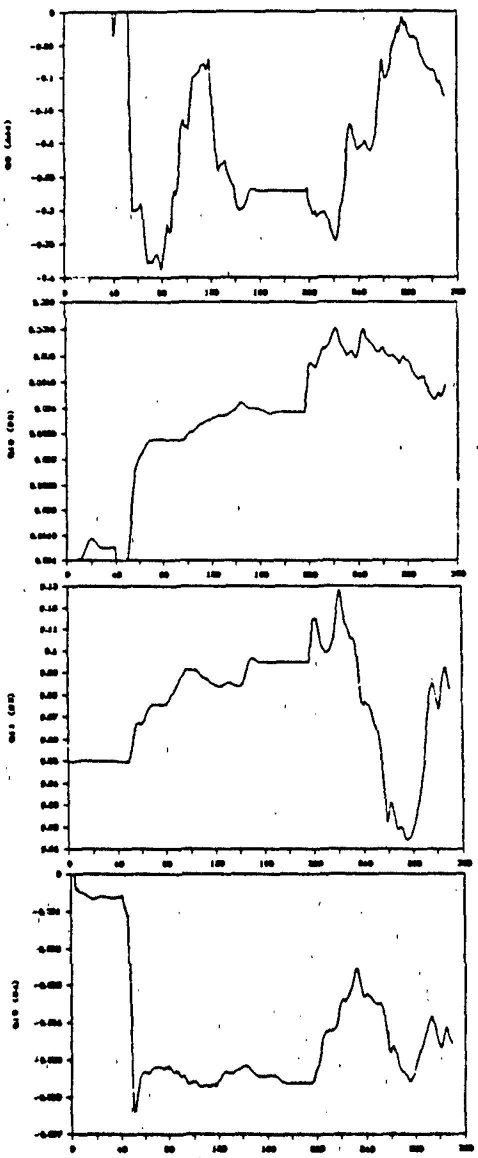

Figure 4: Continued

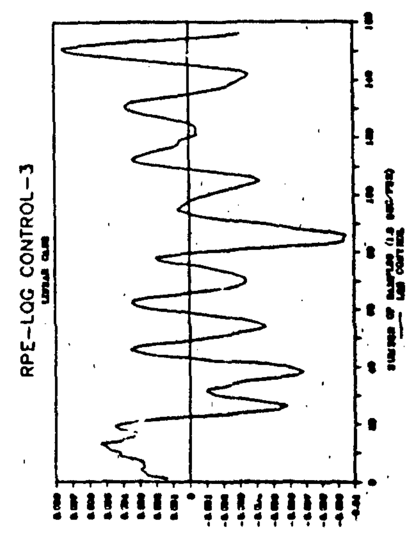

Figure 5: Rudder angles in linear case

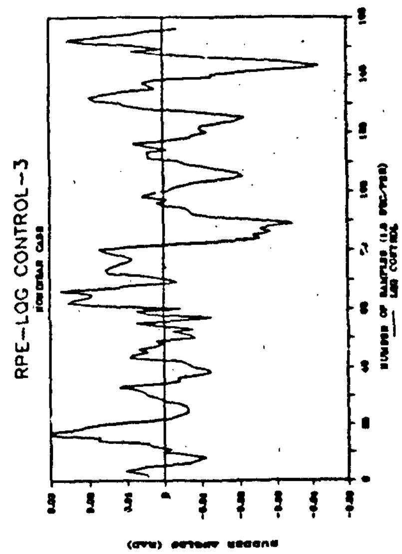

Figure 6: Rudder angles in nonlinear case

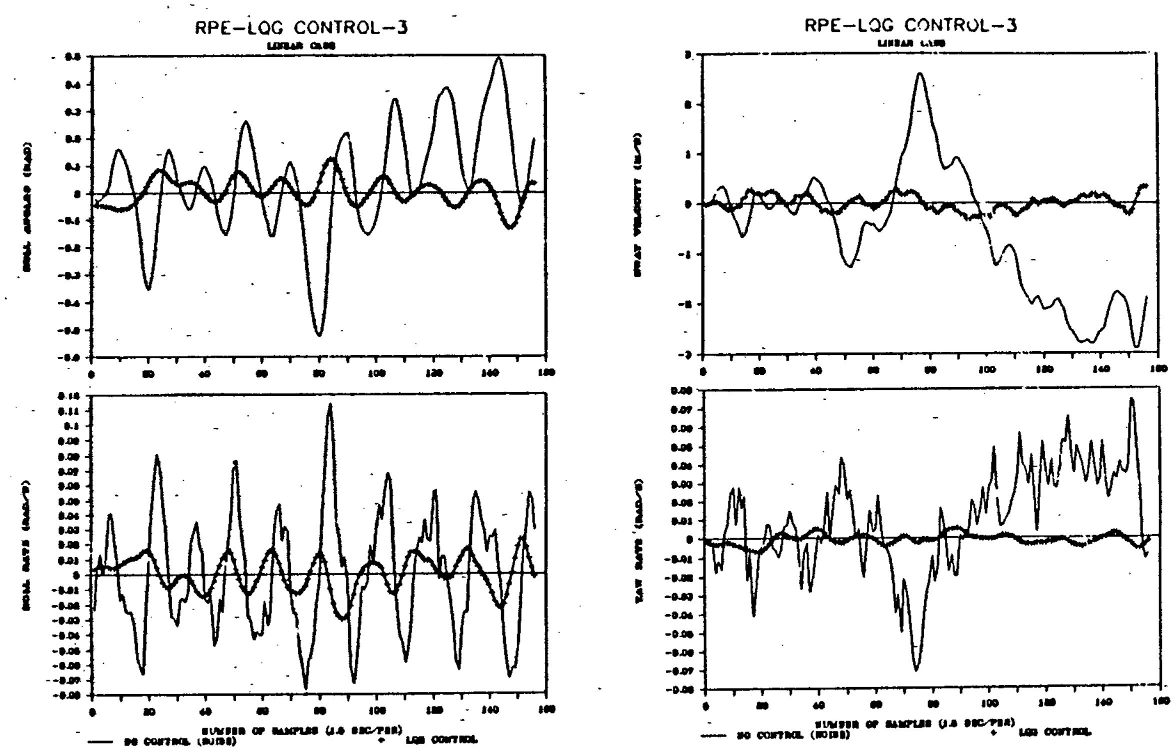

Figure 7: Comparisons of responses with and without RPE-LQG control (linear case)

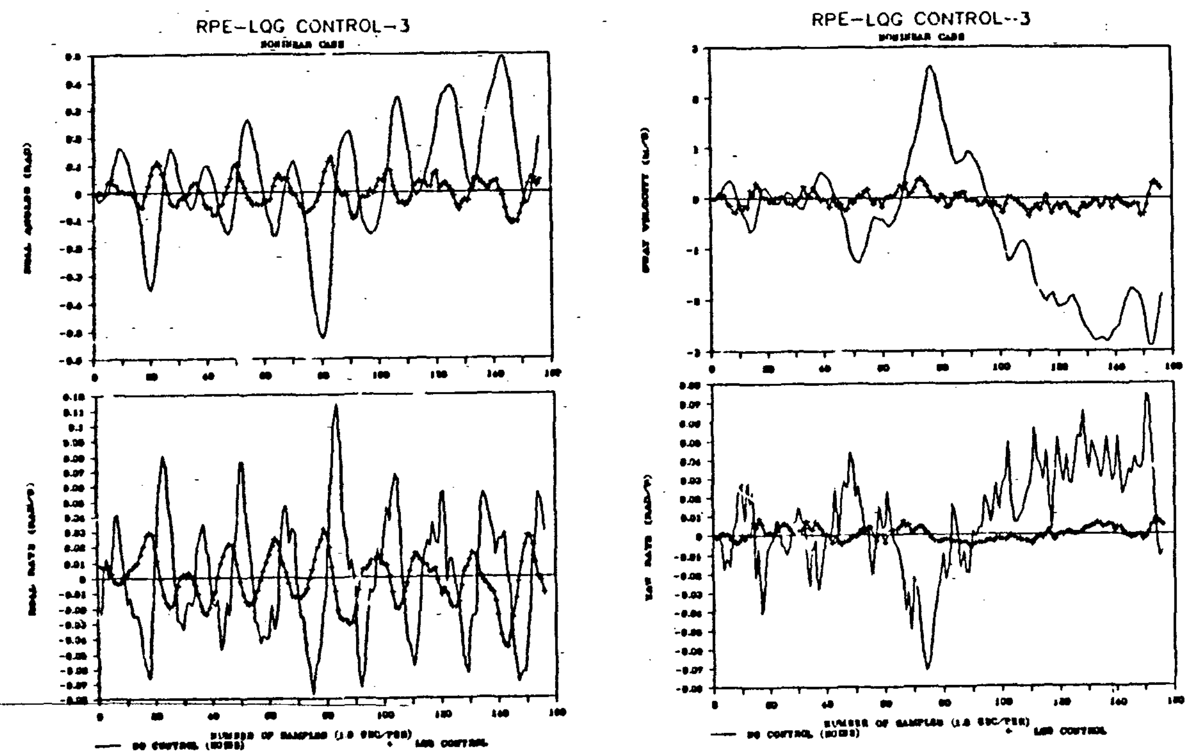

Figure 8: Comparisons of responses with and without RPE-LQG control (nonlinear case)

APPLICATION EXPERIENCES WITH HIGH MANEUVERABILITY RUDDERS

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1. ABSTRACT

Recently, several large oceangoing vessels have been delivered with single and double, high maneuverability rudder systems. These ships had been model tested and now actual performance trial data is available to correlate and provide basic empirical data to improve the accuracy of the model test predictions.

The latest full scale test data indicates that performance of these rudders is better than expected and other major side benefits were highlighted. Such results had been apparent from more than 100 seagoing applications related to smaller coastal vessels, which had not been tank tested.

The particular rudder designs studied are the Schilling Monovec and Vectwin systems. The ships include tankers up to 78,000 DWT, a 185 meter LOA twin screw rail ferry and container and Ro/Ro vessels with speeds of over 20 knots and up to 18,000 HP.

Because of the quick response and high lift of the rudders, particularly the twin rudder system, automation of the maneuvering controls into a single lever joystick allows the ship handler to take full advantage of the many performance benefits available. In fact, the use of the twin rudder system results in a far simpler propulsion/steering control system as the main engines may be run at a constant speed in the ahead direction only, driving fixed pitch propellers. The twin rudder systems alone control the ship's speed and direction.

The results to date suggest the suitability of these high performance rudders for military craft and vessels with tight trackkeeping and/or

dynamic positioning requirements, as well as commercial vessels.

It may now be concluded that high maneuverability rudders are feasible for any size or type of ship, may be readily automated, and offer a cost effective means of improving ship handling capability with no loss of speed or propulsive efficiency.

2. INTRODUCTION

From the time of the first ships or floating platforms, there were no real innovations in ship steering until the 15th century when the steering oar was replaced by a hinged rudder and tiller. This rudimentary rudder design persisted into the 20th century and it was common to see a single centerline rudder installed on a multi-screw steamship. As a result, it was not uncommon that a number of tugs were required to bring a ship into harbor with her engines shut down.

The rudders installed on the large 19th century steamships were limited in their performance because of the great force required to reach the larger rudder angles necessary for effective maneuvering. It was often necessary for the entire crew to man the wheels and the special tackle fitted for the purpose. The development of the balanced rudder alleviated this problem and allowed rudder angles of 35° to 45° to be reached. The rudder still performed, however, in very much the same manner as it had in the past.

The idea that a powered ship must have a rudder activated by the passage of the hull through the water still persists. Only since about 1975 has it been appreciated that what a vessel really requires is a propeller slipstream controller or diverter, not a "ship's rudder" or "steering oar" at all. The steering effect is then no longer dependent on the ship's speed, but on how the thrust of the ship's propeller, or other propulsion device, is controlled.

Many innovative steering and maneuvering systems have been proposed and, in some cases, applied aboard ship. These systems improved the maneuverability of the vessel and were accepted by shipowners to varying degrees. They are, however, often complicated and expensive and

in many cases limited to new construction or to certain types or sizes of ships. They are also often prone to contact damage, particularly when operating in harbors or rivers where large amounts of debris are present or when operating in ice.

Karl Schilling used the idea of controlling the slipstream to develop a design for a high-performance rudder, which produced a remarkable improvement in the maneuverability of Rhine River craft. Since 1975, when it was first fitted to a seagoing vessel, Karl Schilling's fixed geometry high lift rudder concept has found an ever-increasing potential for shipboard applications, a potential not only among smaller inland waterways craft, but also encompassing seagoing ships, particularly coasters and Great Lakes type self-unloaders which need to be more "handy" and which require greater maneuverability than is available from a standard single rudder and propeller. Bow thrusters, for the larger vessels, and various types of specialized rudder propellers and steering nozzles had helped fill this need, but were not the complete solution.

The original fixed geometry high lift rudder design was based on a chord length of 1.3 or more propeller diameters, which required a larger than normal stern aperture. Positive experience with rudders down to one-half a propeller diameter in length, however, has made the fixed geometry high lift rudder suitable for retrofit on virtually any vessel. The single rudder design is known as the MonoVec rudder. It now usually has a chord length of 70 to 80% of the propeller diameter.

Following the success of the single fixed geometry high lift rudder, a design with twin rudders behind a single propeller was developed. By moving the rudders in unison, the single high lift rudder maneuverability is retained, but by moving them independently the output of the propeller can be vectored and its thrust controlled over 360°. This results in an excellent slipstream controller and diverter. The concept works equally well if the propeller is shrouded in a nozzle. A further development is an integrated joystick control to give the necessary positions of each rudder quite simply. The package of independently operable twin rudders and control gear is known as the Vectwin System.

The Schilling Rudders, which are the subject of this paper, will be referred to henceforth as single or twin fixed geometry high lift rudders.

3. PRINCIPLES OF OPERATION

3.1 Background

Historically, some high performance rudders have used mechanical devices which change the geometry of a rudder blade to get larger rudder forces at a given rudder angle. Another variation is to introduce the complication of a powered rotating cylinder at the leading edge of the rudder to improve rudder lift characteristics.

The change of geometry of the rudder is achieved by a hinged flap on the trailing edge which usually is linked to move at twice the rate of the rudder itself. Such rudders were first tried 100 years ago, but have mostly come into use over the past 20 years as the availability of more sophisticated materials allowed improved mechanical reliability for the exposed trailing flaps and operating gear.

3.2 General Description

The basic difference between the fixed geometry design and other high lift rudders is that there are no additional moving parts to the fixed geometry design. The patented design, shown in Figure 1, has five essential features:

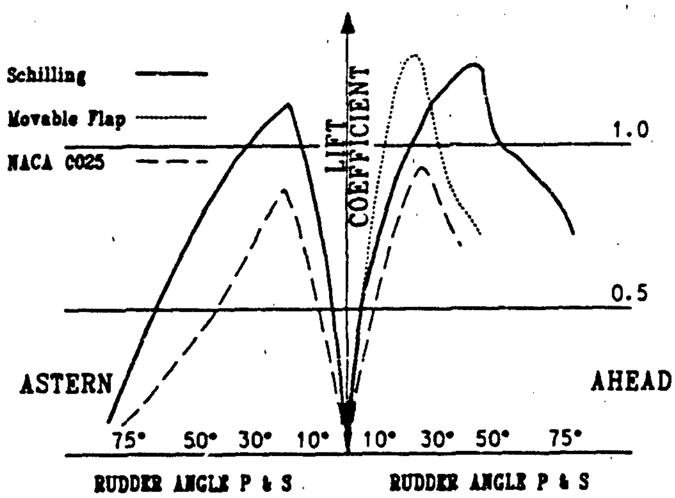
1. There are no moving parts other than the single piece blade.
2. The rudder operates at angles in excess of 45° and preferably not less than 2 x 65°.
3. It has a high lift leading section with rounded entry to delay the onset of stall.
4. It is fitted with top and bottom horizontal boundary plates or fences to contain the deflected propeller slipstream and to reduce spillage.
5. The ruddar design includes a "Wedge" geometry at the trailing edge to encourage a clean exit flow, Ref. (1).

The fixed geometry high lift design emerged around 1965 after many years of experimentation with other high lift rudders, flap rudders, shutter rudders, etc., on vessels in European Inland Waterways.

Figure 1. Single Fixed Geometry High Lift Rudder

3 3 Comparison With Flap Type Rudder

When tested in a circulating water channel, there is not much difference in the ahead direction lift characteristics of high lift rudders, except for the angles at which peak lift occurs, Figure 2.



	SCHILLING RUDDER	CONVENTIONAL RUDDER (NACA 0025)
Velocity	2.0 m/s	2.0 m/s
Area	0.103 m^2	0.125 m^2
Taper	1.0	1.25
Aspect Ratio	0.863	0.96
Reynold's No.	0.804×10^6	0.619×10^6

Test Results by HSVA Hamburg

Figure 2. Comparison of Lift Coefficients for Rudders of Various Types

It has been observed, however, from similar vessels, one with a flap rudder and the other with a fixed geometry high lift rudder, that the turning circle is smaller for the latter. The reason for this is that the lift/drag ratio at all angles of attack for a rudder with a tail flap is less than that for an unflapped rudder, Ref. (2).

Consider a vessel crabbing or turning at rest, which is essentially the main purpose of high lift rudders. With a flap rudder at 45° and the fixed geometry high lift rudder at 65°, the flow from the propeller is deflected by the angle of attack of the rudder and is also affected by the rotation or sideways motion of the vessel, Figure 3.

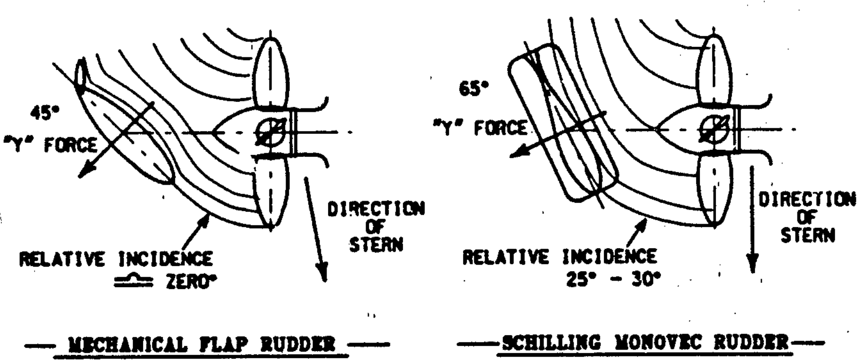


Figure 3. Dynamic Flow Lines When Rotating or Crabbing

During such a maneuver with the flap rudder at 45°, the relative incidence approaches zero while, with the fixed geometry high lift rudder, there is still an advantageous angle of attack. This, combined with its unchanged geometry, produces a stronger "Y" force to sustain the turn or crabbing motion than the flap rudder. Therefore, for comparative tests, a free floating model will be more representative than the comparison of reaction forces on a fixed model.

3.4 Rudder Design

Other design aspects of the fixed geometry high lift rudder offer secondary, but still significant effects. The trailing wedge induces a course stabilizing influence to offset yaw. The trailing wedge also reacts on the propeller swirl as a contra rotational fixed vane. Both of these aspects probably contribute to the excellent full size trial propulsion results which have been consistently obtained.

The top and bottom plates also help to straighten propeller swirl. These plates, being single section, also offer some protection to the rudder-body against impact damage.

The fixed geometry high lift design has also been developed as double rudders for use where fore and aft length is at a premium. These handed rudders, with a shortened chord length, are operated in unison to give

similar maneuverability as the standard single fixed geometry high lift rudder, Figure 4.

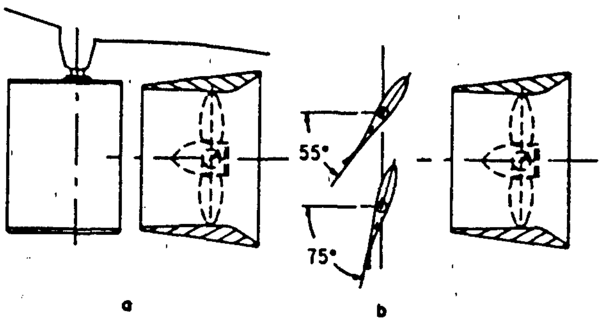


Figure 4. Double Fixed Geometry High Lift Rudders
(total travel 130°, 75° outbd. - 55° inbd.)
a. Double High Lift Rudder Profile
b. Plan View at Full Helm to Starboard

The twin fixed geometry high lift rudders have been further developed to be used where each rudder is controlled separately to give 360° directional control to the propeller slipstream, Figure 5.

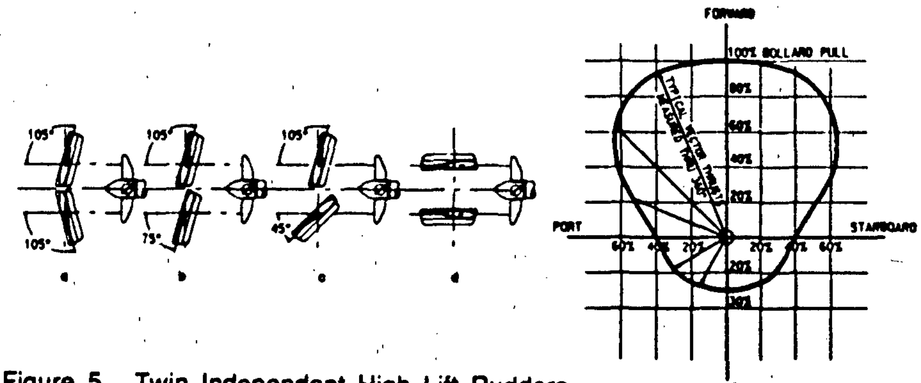


Figure 5. Twin Independent High Lift Rudders
a. Astern, b. Astern to Port, c. Stern to Port
d. Ahead, e. Thrust Vector Diagram with Joystick Control

Essentially, the height of a fixed geometry high lift rudder blade is related to the propeller disc. A more apt description of the device may well be "slipstream controller" rather than the term "ship's rudder".

4. SINGLE FIXED GEOMETRY HIGH LIFT RUDDER EXPERIENCE

The specific benefits arising from the use of a single fixed geometry high lift rudder can be considered under several categories:

1. Turning circle characteristics
2. Side thrust for "spot turning"
3. Side thrust for "crabbing"
4. Yaw checking ability
5. Course keeping ability
6. Initial turning ability
7. Astern performance

4.1 Turning Circle Characteristics

a. Definitions Advance - The distance traveled by the vessel in the original direction of travel (usually measured when the vessel has altered course by 90°).

Transfer - The distance, at right angles to the original track, through which the vessel has moved. The datum point for advance and transfer is usually the point at which the helm has been put hard over.

b. Turning Capabilities From a "ship at rest" situation, the fixed geometry high lift rudder enables a vessel to rotate on the spot. With a vessel underway, the turning circle with the helm hard over is not greatly affected by the speed of entry. On one vessel, recently, it was found that the track at a speed of entry of 15 knots was almost identical to the track at speeds of entry of 10 knots and 5 knots.

Due to the initial braking effect of a fixed geometry high lift rudder used at high angles, the speed through the water is rapidly reduced and the "advance" and "transfer" are very much less than for a vessel with any

other type of rudder. Typically, a 100 m (328 ft.) vessel at a speed of entry of 16 knots would have turned through 90° after an "advance" of about 2.2 ship lengths and with a "transfer" of about 1 ship length. At a speed of entry of 10 knots, the "advance" would be about 1.8 ship lengths and "transfer" 0.7 ship lengths.

This results in the vessel having the ability to cease "advancing" (that is, stop) by maintaining full power ahead and using the fixed geometry high lift rudder to turn the vessel. The "advance" or stopping distance by that maneuver is usually about half of the distance required to stop the vessel by reversing the engine or CP propeller. Since a reversing propeller often causes the vessel to veer wildly off course, the odd situation arises that the "transfer" is often also reduced by using the fixed geometry high lift rudder in this way.

Typical turning circle data for the M/V "Oresund", a 15,000 tonnes displacement, twin screw, railroad ferry, are shown in Figures 6A and 6B.

4.2 Side Thrust for "Spot Turning"

As much as 50-70% of ahead thrust may be generated at right angles to the hull with no ahead thrust remaining, enabling the fixed geometry high lift rudder to act as a powerful stern thruster. The helm angle at which such thrust occurs is between 50° and 70° depending on the chord-length of the rudder, Figure 7.

4.3 Side Thrust for "Crabbing"

When used in conjunction with a bow thruster, the vessel can be moved sideways or "crabbed". The limiting factor for crabbing speed is normally the power of the bow thruster.

4.4 Yaw Checking Ability

The fixed geometry high lift design has a very effective yaw checking ability as is demonstrated in the following model tests on a 175 m twin screw ferry at Vienna, Figure 8, and a 109,000 DWT O.B.O. vessel at Trondheim, Table 1.

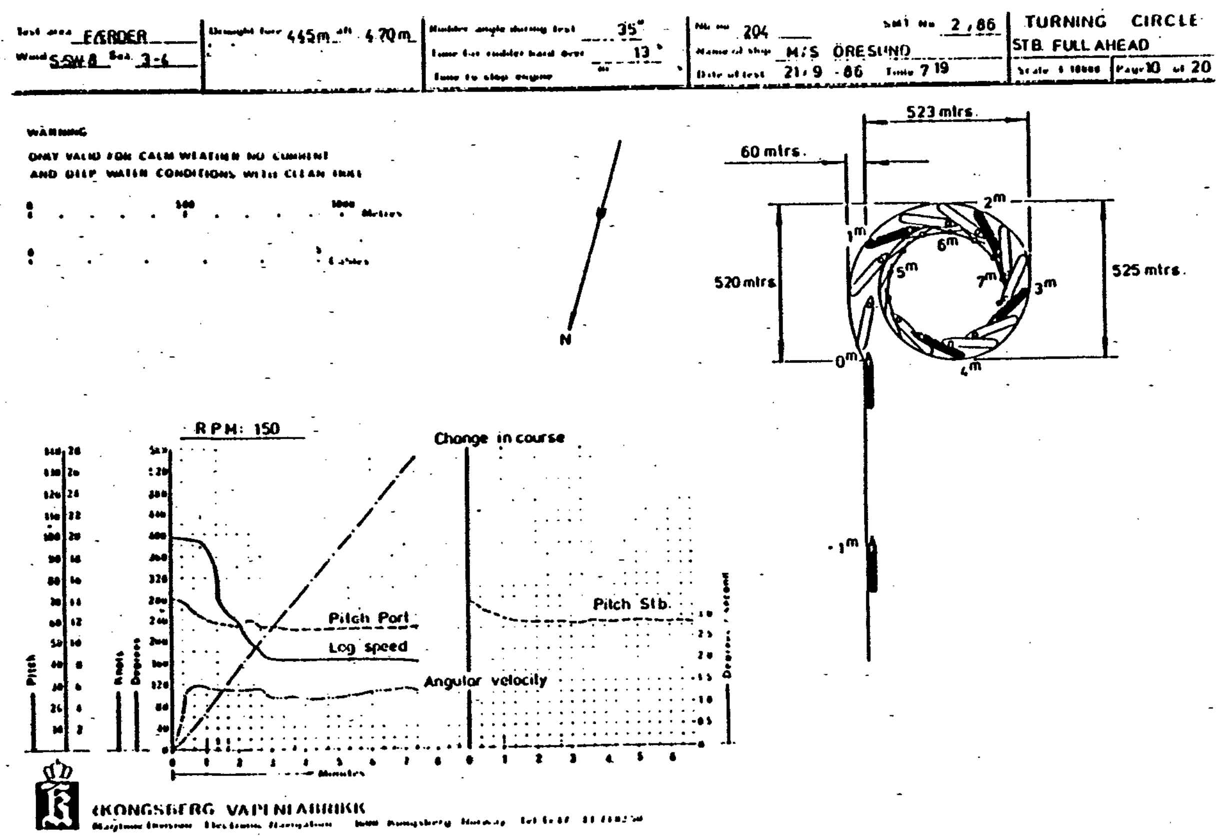


Figure 6A. Trial Report Excerpts - M/V "Oresund"

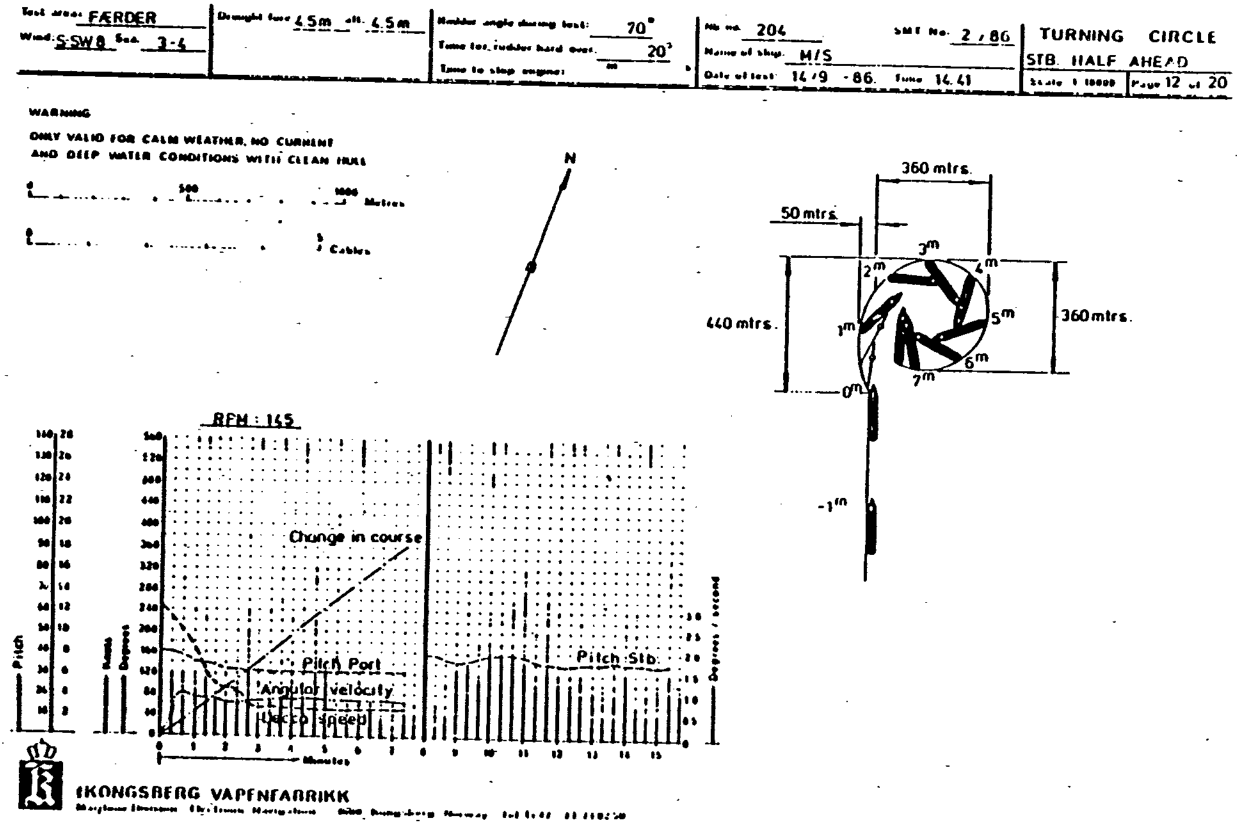


Figure 6B. Trial Report Excerpts - M/V "Oresund"

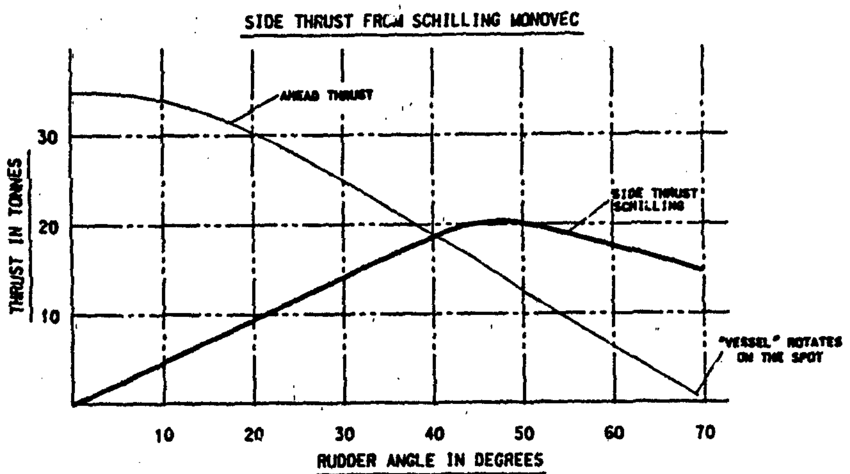


Figure 7. Ahead Thrust vs. Sidethrust from Diverted Propeller Slipstream, Single Fixed Geometry High Lift Rudder

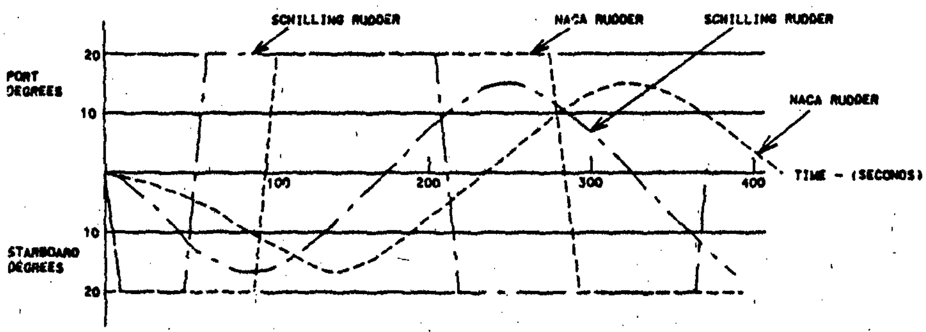


Figure 8. Slow Steaming Ability - 6 Knot Zigzag Maneuver Model Test for 175 M Twin Screw Ferry (Vienna Model Basin) 20°/10° Zigzag Test

Table 1. Model Test Result (Trondheim) 109,000 Tonne O.B.O. Showing Yaw Checking and Course Keeping Single Fixed Geometry High Lift Rudder

Rudders	Conventional	Large Conventional	Fixed Geometry High Lift
Dimensions (l x h)	5.9 x 9.8	6.8 x 11.8	6.65 x 9.0
1. Initial Turning Time For 10°/10° Zigzag	1.62 secs.	1.57 secs.	1.66 secs
2. Yaw Checking Time 10° Rudder Angle	3.68 secs.	2.25 secs.	1.11 secs.
3. Overshoot Angle 10° Rudder For 10° Ship's Heading Change	18.6°	10.9°	7.1°
4. Spiral Hysteresis Loop	expected	expected	no hysteresis

4.5 Course Keeping Ability

The Trondheim and Vienna model tests also show that the course keeping qualities of the fixed geometry high lift design are excellent. The trailing edge geometry inherently acts as an anti-yaw device. The high lift profile requires very small helm angles for course correction. The Trondheim model tests indicated that the 109,000 DWT O.B.O., which was dynamically unstable with a conventional rudder, was improved to such an extent, by fitting a single fixed geometry high lift rudder, that all hysteresis was eliminated.

4.6 Initial Turning Ability

The high lift characteristics of the fixed geometry high lift rudder reduce the response time to generate initial turning and promote effective handling. This was demonstrated during the trials of the FPV "Leonard J. Cowley" on the Canadian Forces Maritime Experimental and Test Ranges, Figure 9.

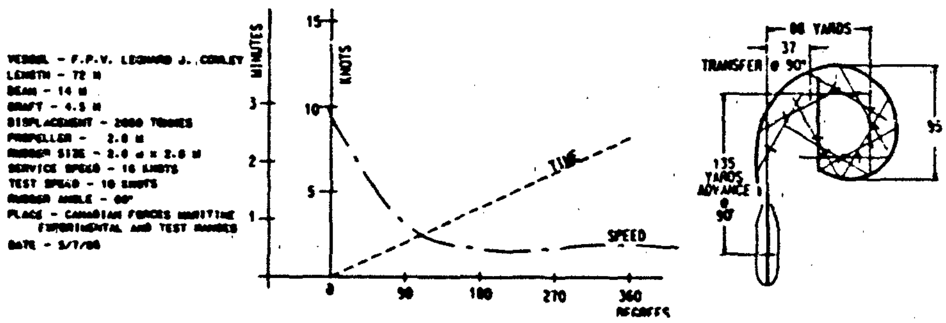


Figure 9. Typical Turning Curve (single fixed geometry high lift rudder)

4.7 Astern Performance of Single High Lift Rudders

The fixed geometry high lift rudder design obtains outstanding maneuverability by deflecting the propeller slipstream. This is only ible in the "ahead" mode of propeller operation.

In the "astern" mode, the rudder acts in the same manner as a conventional NACA rudder. It will be seen from Figure 2 that the "lift" coefficient of the fixed geometry high lift rudder in the "astern" mode is about 30% better than for the conventional NACA shape. Both rudders stall at about 20° rudder angle and there is little point in using greater angles than this when going astern with a single screw vessel. Flap type rudders were not tested astern since the flap shape stalls at very small angles going astern.

With twin screw vessels, the "crabbing" effort from single fixed geometry high lift rudders is more powerful than with conventional

rudders. The rudders can be used at about 50° with one propeller ahead and the other astern. Forward movement of the vessel can be prevented with very much less astern power than is necessary with conventional rudders.

4.8 Fixed Geometry High Lift Rudder Experience from a Shiphandler's Perspective

An increasing number of vessels, ordered in recent years, have specified high efficiency rudders. Such rudders can be necessary for particular vessels in certain trades, where demanding docking maneuvers in severe conditions would not be safe without them. When the Swedish State Railway Company was planning to build a new twin screw, twin rudder, railway ferry for the 21 nautical mile route between Helsingborg, Sweden and Copenhagen, Denmark, simulator studies indicated that conventional spade rudders would not provide sufficient manueverability.

Even after adding a powerful stern thruster to the simulator program, the maneuverability was still not considered sufficient and the owners looked into high efficiency rudders. As this vessel had to operate in severe ice conditions, single fixed geometry high lift rudders were considered the most suitable because of their one-piece construction.

A further simulation was carried out with two single high lift rudders. This change made a significant difference as the masters involved with the simulation, found it much easier to handle the vessel. The owners were then satisfied that the performance of the vessel would permit safe operation under severe wind and current conditions in the restricted harbors.

The "Oresund" was delivered in November, 1986 fitted with single fixed geometry high lift rudders and has been in successful operation ever since. The stern thruster was retained as an additional maneuvering device. Early in 1990, the stern thruster broke down and, as the masters consider it redundant, it will not be repaired until the "Oresund" is on a dry dock, which is not planned until 1991.

Operational experience has shown that the masters can easily cope with conditions far worse than programmed into the simulator. The

"Oresund" has operated in winds up to 50 knots. The "limiting" factor in these conditions has been the 32 tonnes combined output of the two bow-thrusters. "Crabbing" the stern at those wind velocities, whatever the wind direction, is no problem, according to the masters.

The winter of 1986-87 was much colder than normal and the entire Swedish and Danish coasts were covered by a thick layer of ice. The very strong currents in the straits between Sweden and Denmark caused large ice-walls which the "Oresund" had to force six times a day. Also, the turning basins were crowded with large ice blocks making berthing very difficult. The masters claim that they would not have been able to keep their tight schedules if the vessel had been equipped with conventional rudders. With the high lift rudders hard over, they were able to use main engine power to swing the stern in and out to clear ice from the berth.

Vessels with two propellers and two rudders turn on the spot using one propeller working ahead, the other astern and the two rudders hard over. With conventional rudders, you can only use 50-70% power on the propeller working ahead as the propeller working astern cannot neutralize all the ahead force.

On the "Oresund" with the more efficient high lift rudders, it is possible to use full power on the propeller working ahead while only low power is required on the propeller working astern, as the rudders at full helm, 70°, eliminate almost all headway, allowing the vessel to swing on the spot. In this situation, you can also choose to work the rudders at 40° where they give maximum lift, causing some headway, but still within the range that can be counteracted by the propeller working astern.

The masters of the "Oresund" normally turn by putting both rudders hard over with both propellers working slow or half ahead causing the vessel to turn virtually "on the spot". With twin independently operable rudders and twin propellers, both rudders may be turned inboard to maneuver solely by working one propeller ahead and the other astern. This method allows very fast maneuvering without moving the rudders. Supply vessels often use this method when they work close to off-shore rigs. Highlift rudders are a distinct advantage in this situation. High efficiency rudders also allow the use of outward rotating CP propellers

for better propulsion efficiency while retaining good maneuvering performance

The advantages are not limited to maneuverability or the response from the rudder for [illegible] course keeping at sea. The skeg [illegible] the rudder and the rudder's trailing "wedge" contribute to an increase in the dynamic stability of the vessel, which, in combination with the rudder's high efficiency profile, means that only very small rudder movements are necessary for course correction. With rudder angles of 65°-70°, one would expect that a vessel would heel dramatically during a turn at full speed. This is not so because the rudder, at these angles, acts initially as an effective brake to reduce the speed.

On the "Oresund's" trial trip, concern about too much heeling during a turn at 70° rudder angle caused the yard to limit the initial speed for this turn to 13 knots. Everyone was pleasantly surprised that there was almost no heel.

When the 17,000 DWT, single screw passenger/container vessel, "Americana", also equipped with a single fixed geometry high lift rudder, used a rudder angle of 70° with an initial speed of 19.3 knots on her trial trip, she did not heel more than 3° at any time. If a smaller rudder angle, say 30°, had been used, the heel would have been greater as the speed is not reduced as quickly.

Thus a fixed geometry high lift rudder may be used to turn a vessel "out of danger" with far less likelihood of causing dangerous heel than if fitted with a conventional rudder, but full helm must be used, see Figures 10 and 11.

As the rudder speed is normally 4°/sec. or faster, the initial rudder force phase, which causes snap-roll, will be short. When the rudder has reached 65° or 70°, the drag coefficient is high (1.15) and the lift coefficient is low (0.55). Also, the rudder force at these helm angles is not high enough to promote snap-heel. Until the ship's speed slows and lateral movement of the stern occurs, the relative flow angle on to the rudder blade does not reduce. Thus the drag coefficient remains high and the lift coefficient low.

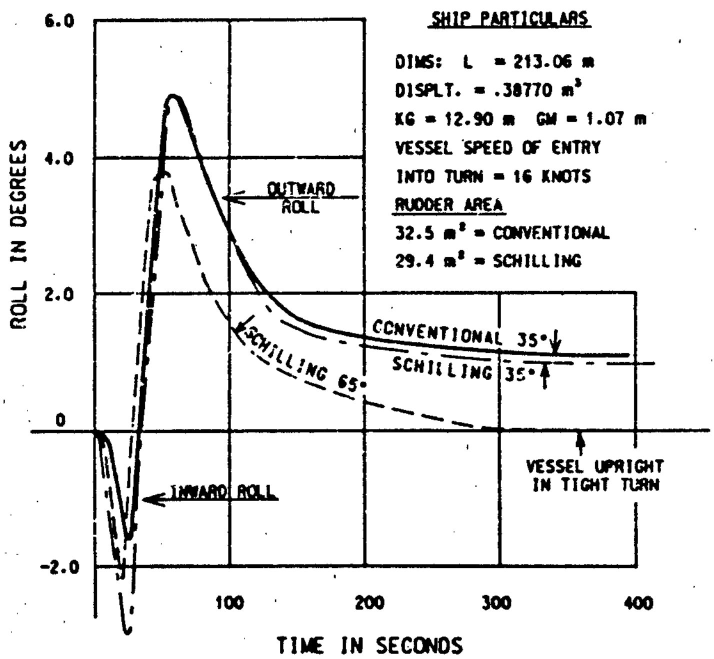


Figure 10 Comparative Heel - High Lift Rudder vs. Conventional Rudder

In the final phase of the turn, the center of gravity of the vessel will be virtually stationary as the vessel rotates on the spot. With no forward velocity, no centrifugal force is generated to cause outward heel. Once this phase is reached, the relative incidence of the slipstream will be about 30°. At this point, the lift coefficient is nearing its maximum and the drag coefficient is reduced to a negligible figure so that the rudder is operating at close to maximum efficiency.

Therefore, there is much less danger of capsizing a "tender" vessel in an emergency situation when using high efficiency rudders at their maximum excursion than when using rudders at smaller angles. For major course alterations during normal navigation, it is advantageous if the autopilot is capable of executing constant radius turns. Selection of a large radius will minimize speed-drop and heel.

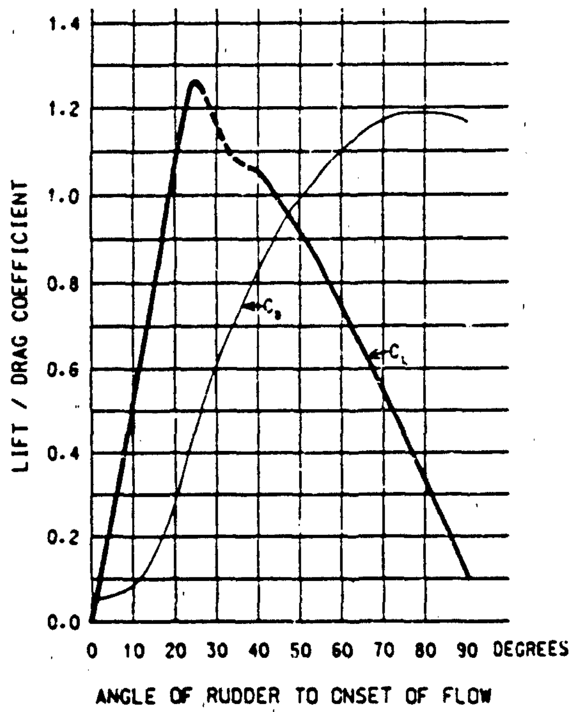


Figure 11 Hydrodynamic Characteristics Single High Lift Rudder With Flat Root and Angled Tip End Plates (Circulating water channel)

Some comments on the mechanics of heeling may be appropriate to further explain this observed performance in high speed turns. The rudder force, which is the first transverse force to become effective after the rudder is put to a particular angle, causes the vessel to heel inwards in a turn. When a drift angle develops and the hull starts to rotate, the centripetal component of the hull resistance and the centrifugal effect of the vessel's inertia first cause the inward heel to decrease . As the vessel enters the second phase of the turn, these forces then cause the vessel to heel outwards. The greatest heel angle is reached immediately after the change from inward to outward heel, because, due to inertia, the vessel rolls further than the static equilibrium position. At this stage, the rudder force partially counteracts the centrifugal force and thereby

decreases the heel. If the rudder suddenly is put to midships or, even worse, to a counter position, dangerous heel angles can occur as both the rudder and centrifugal heeling moments now work in the same direction. This must be kept in mind when turning a vessel with a high efficiency rudder which has a very steep lift curve, such as a mechanical flap rudder.

5. COMPARATIVE SEA TRIAL DATA

This section presents comparative data obtained from sea trial results of sister ships equipped with fixed geometry high lift rudders and NACA or flap rudders.

5.1 "North King" and "North Empress"

Table 2 shows the sea trial results from the 76.8 meter LBP "North King" and "North Empress", built by J. J. Sietas of Hamburg for Antares Shipping of London. The "North King" is fitted with a fixed geometry high lift rudder and the "North Empress" with a flap rudder. Note the better propulsion performance and turning circle of the single fixed geometry high lift rudder compared with the flap rudder.

Table 2. Comparative Rudder Performance Data, "North King" and "North Empress"

	Flap Rudder	Fixed Geometry High Lift Rudder
Draft	Ballast	Ballast
Power	2152 KW	2090 KW
Speed	13.23 Knots measured mile	13.7 Knots
Rudder Angle	2 x 45°	2 x 65°
Turning Circle	94 m (average P & S)	72.5 M
Time for 360°	2 min. 30 secs.	2 mins. 16 secs.

5.2 "Kozan Maru" and "Rocco Maru"

Figure 12 shows the sea trial results from the "Kozan Maru" and the "Rocco Maru", built by Shinhama Shipyard in Japan. The "Kozan Maru" is fitted with a fixed geometry high lift rudder and the "Rocco Maru" with a NACA rudder. Note, particularly, the difference betw3en the fixed geometry high lift rudder and the NACA both at 35° helm angle.

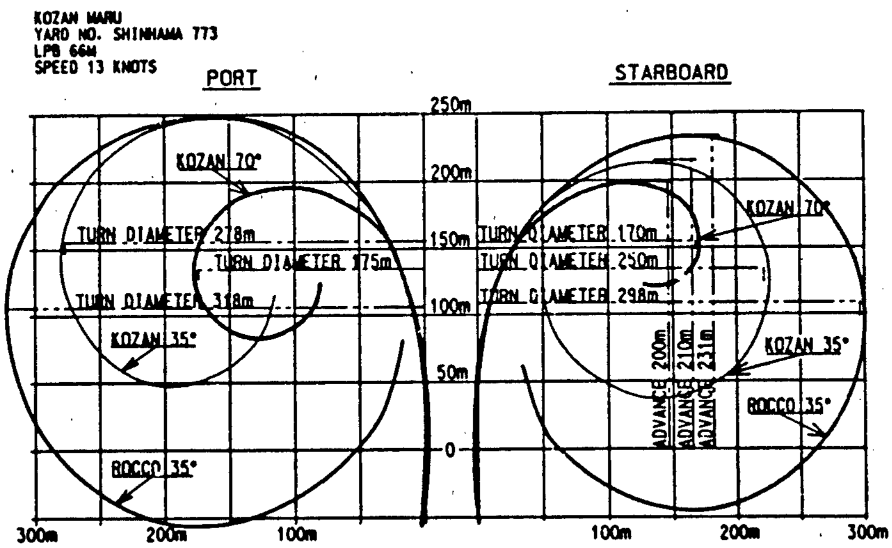


Figure 12. Sister Ships "Rocco Maru" Equipped with a NACA Section Rudder and "Kozan Maru" Equipped with a Fixed Geometry High Lift Rudder.

5.3 "Tress Pioneer" and "Concordia"

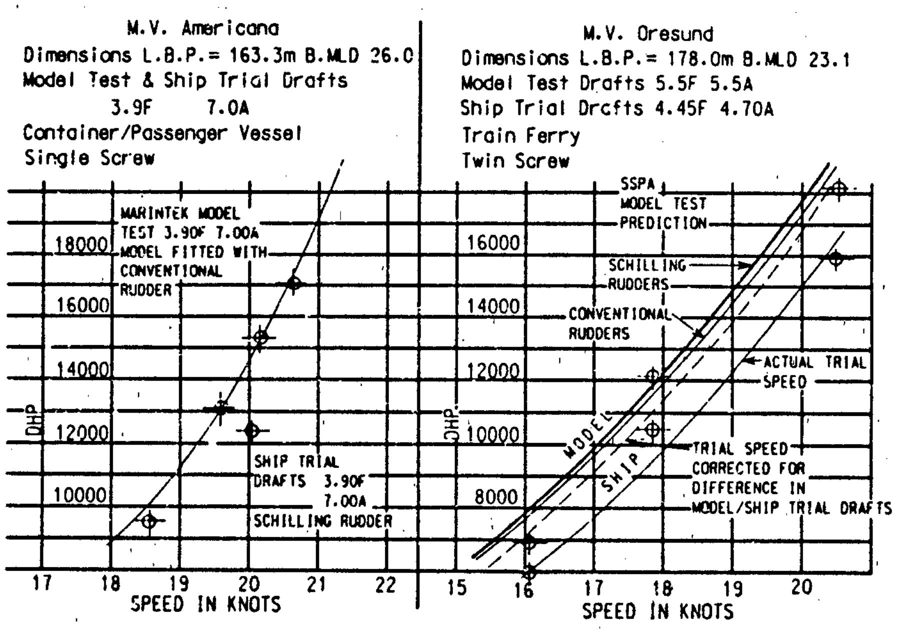
Trial speed results from two similar trawlers of 59 m length, built by the Langsten Shipyard in Norway, are presented below. The "Tress Pioneer" is fitted with a fixed geometry high lift rudder and the "Concordia" is fitted with a flap rudder.

"Tress Pioneer"	100% MCR	Trial speed 15.4 knots
"Concordia"	100% MCR	Trial speed 15.15 knots

6. COMPARISON BETWEEN MODEL TESTS AND SHIP TRIAL RESULTS (SINGLE FIXED GEOMETRY HIGH LIFT RUDDER)

On a number of occasions, a fixed geometry high lift rudder has been fitted to a vessel after the model had been tested with a conventional rudder. Typical of these is the M/V "Americana" whose trial results were identical to the predictions for the vessel with the conventional rudder, Figure 13. On several occasions, the trial speed has been in excess of the model prediction and there never has been a speed deficiency.

In the case of the twin screw ferry, M/V "Oresund", the model was tested with conventional rudders and with fixed geometry high lift rudders. The model results for speed indicated slightly in favor of the conventional rudder. Ship trial results for the vessel with fixed geometry high lift rudders were better than predicted, Figure 14.



Figures 13. and 14 - Model vs. Trial Results

Every retrofit with a single fixed geometry high lift rudder has resulted in a significant improvement in maneuverability without any loss of ship speed. In several instances, an increase in ship's sea speed has also been noted. On two occasions where identical vessels have been built, one with a flap rudder and the other with a fixed geometry high lift rudder, the vessel with the fixed geometry high lift rudder has proved to be the faster.

Part of the explanation is that the fixed geometry high lift rudder promotes better course keeping. This is clear from model tests and seagoing experience. With the rudder amidships, the tailfin of the fixed geometry high lift rudder would appear to have a slightly higher drag coefficient than a flap rudder. With a very small rudder angle, however, the situation is reversed and the drag coefficient of the fixed geometry high lift rudder is much lower, Figure 15. On any single screw vessel, a small helm angle is required to compensate for asymmetric propeller forces. This, coupled with the better course keeping, helps explain the improvement in speed achived with the fixed geometry rudder.

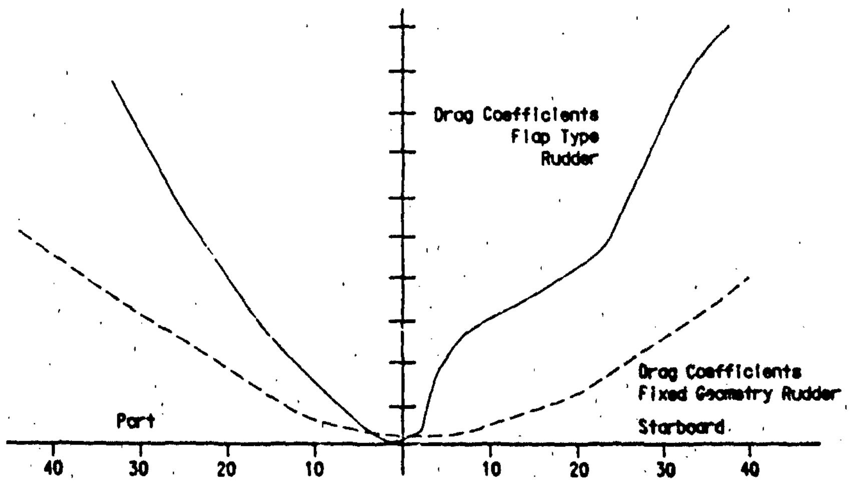


Figure 15. Typical Curve of Drag Coefficient for Fixed Geometry High Lift Rudder Compared With That For Flap Rudder. Source - Model Tests in Propeller Slipstream. Fixed Geometry High Lift Rudder - V(s) = 7.396 m/s Flap Rudder - V(s) = 7.755 m/s.

7. TWIN RUDDER EXPERIENCE

The entry into service in September, 1989 of the 32,000 DWT Caltex Tanker, M/V "Australia Sky", Figure 16, marks a considerable increase in the size of ship to be fitted with the joystick controlled twin high lift rudder system. The owners have reported most favorably on the degree of maneuverability achieved and expect to save 70% on harbor tug assistance. The harbor tug cost for the previous conventional rudder tanker was $350,000 (U.S.) annually.

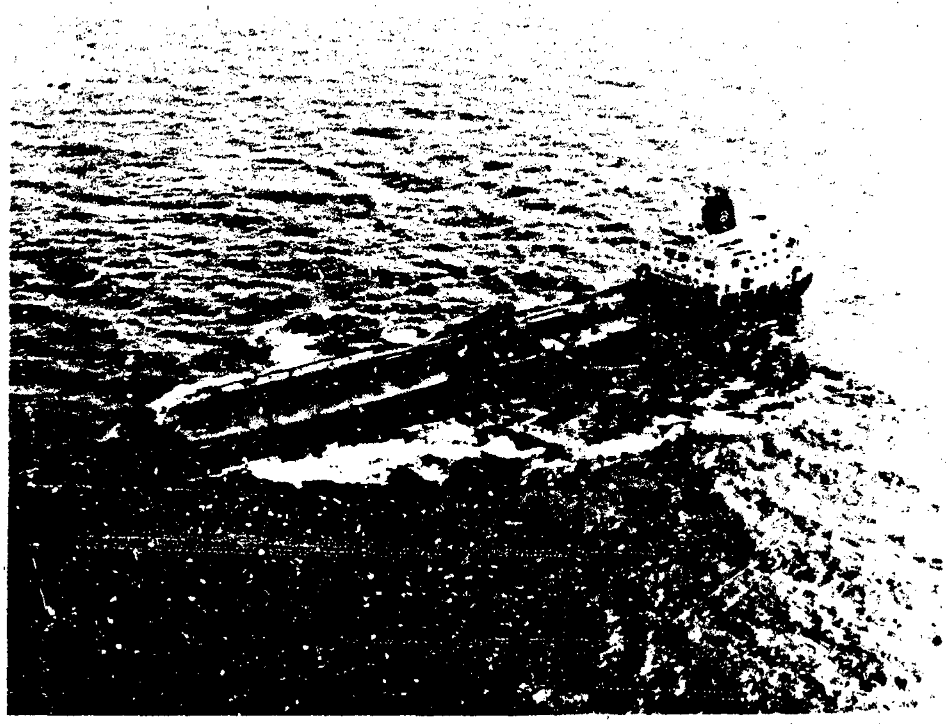


Figure 16. M/V "Australia Sky"

For the twin rudder system, two fixed geometry high lift spade rudders are used with a single fixed pitch propeller, continuously rotating ahead. They are coordinated by a single joystick to direct the slipstream to give 360° thrust capability over the entire speed/power range. The main engine on the M/V "Australia Sky" is a longstroke slow speed Burmeister and Wain Type 5LM60.

Previously, the largest vessel was the 12,000 DWT cement carrier, M/V "Milburn Carrier II", Figure 17, which is also fitted with a fixed pitch propeller and, additionally, a shaft driven generator. The main engine is a Burmeister and Wain Model LM42.

Figure 17. Twin High Lift Rudder M/V "Milburn Carrier II"

The progression up the tonnage scale confirms that the twin high lift rudder system is applicable to larger vessels. Design studies have been completed for vessels up to 270 m length and in excess of 200,000 tonnes displacement.

The propulsive performance of the M/V "Australia Sky"; which is the fifth seagoing vessel now in service to be fitted with twin high lift rudders, indicates that the speed/power curve is similar to a single conventional rudder ship.

The twin high lift rudder system, associated with the higher efficiency of a fixed pitch screw, is a fuel efficient propulsion system by any standard. Another economic aspect is the exceptional course stabilizing effect of the rudders. The reliability of the system has been clearly demonstrated by the single, fixed pitch propeller Ro/Ro ferry, M/V "Belard", displacement 3000 tonnes, operated by P&O on the daily Belfast/Ardrossan run where utilization has been high. The captains, who previously operated twin screw CP propeller ships, admit readily that they prefer the degree of maneuverability of the twin high lift rudder system on the M/V "Belard", particularly when operating in and out of the limited space available at Ardrossan, see Figure 18.

The owners report that this vessel carries twice the cargo of the previous smaller twin screw ferry which the "Belard" replaced and with reduced fuel consumption, a very good indicator that a centerline fixed pitch propeller is far more economical than the twin CP propellers previously needed for maneuverability. The "Belard" was retrofitted with twin high lift rudders (a single flap type rudder was previously fitted) and the owners report that the original trial speed is easily achieved and, if there has been any change in propulsive performance, it is for the better.

With the ever increasing accent on operational safety, particularly for large tankers, the two completely independent rudders offer the only standard system totally to satisfy the IMO recommendations for steering system redundancy.

The next vessel to be fitted with twin high lift rudders is the oceangraphic and survey vessel under construction at Bazan, Cartagena.

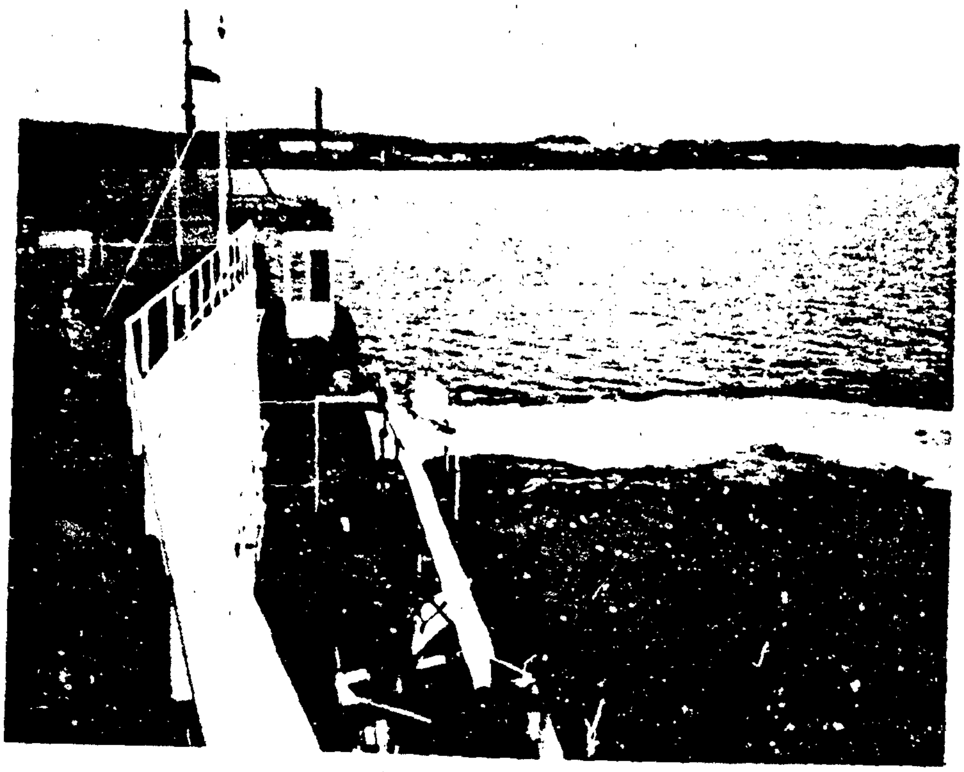


Figure 18. M/V "Belard" Twin High Lift Rudders "Stern to Starboard"

In cooperation with the College of Maritime Studies at Warsash, Southampton, the 1/40 scale manned model of a 225,000 tonne tanker has been retrofitted with twin high lift rudders, Figure 19. The model is kept at their Marchwood Lake facility and the operators consider that this model demonstrates that the twin independent rudder system provides a degree of control for large tankers which is far more effective than other maneuvering systems in overcoming the problems associated with handling these large vessels.

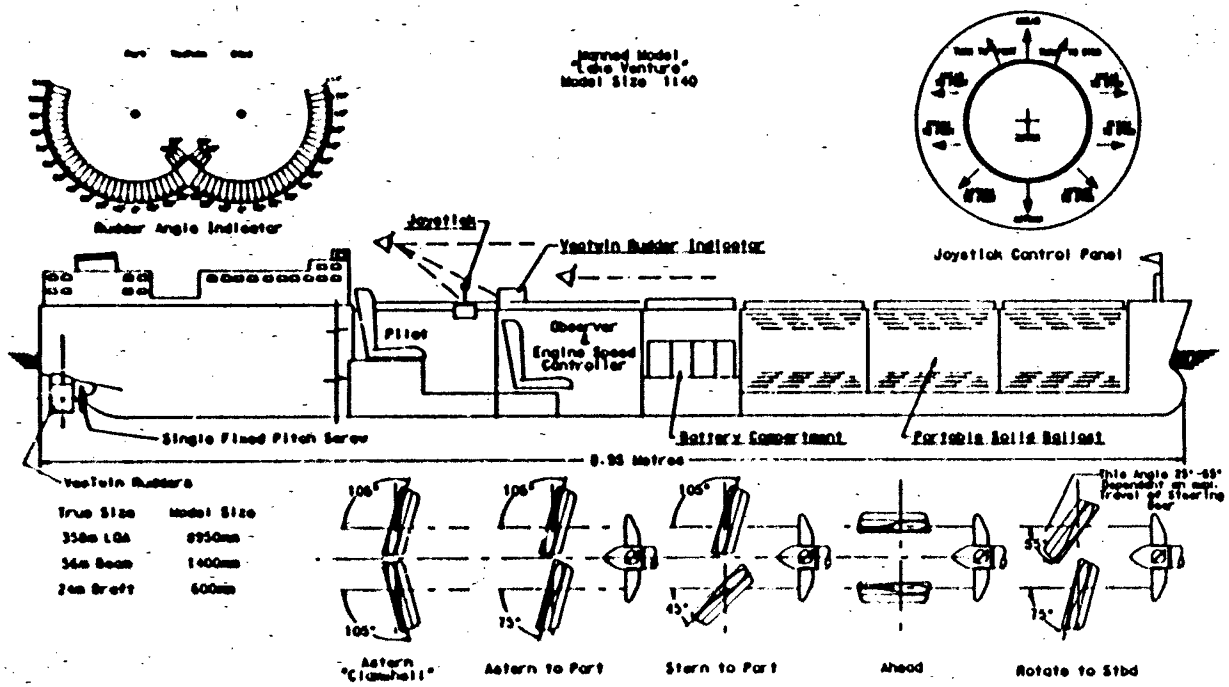


Figure 19. Manned Model "Lake Venture", Displ. 225,000 Tonnes
Twin High Lift Rudders, Single FP Screw Product Carrier

8. COMPARISON BETWEEN MODEL TESTS AND SHIP TRIAL RESULTS (TWIN HIGH LIFT RUDDERS)

Ship model tests exaggerate the resistance of any appendages fitted to the model. One reason is that the appendages are small in size with a very low Reynolds number. With a twin high lift rudder system, a further factor is that the model rudders lie outside the boundary layer aft of the ship. It appears that some variation to the 1978 ITTC performance prediction method is required. On a model test at SSPA, the resistance was corrected by allowing for the local Reynolds number of the rudder itself. This resulted in a good ship/trial model test correlation. Other model tests using the standard method have produced predictions which proved to be pessimistic. Figure 20 shows one test where the ship trial result was 16% better than model test prediction.

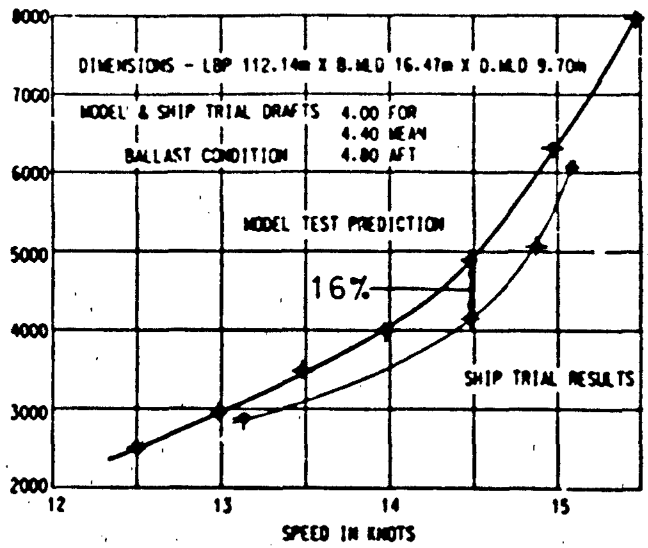


Figure 20. Twin High Lift Rudders Seatrial Model Test Comparison

The maneuvering test results from freely floating remote controlled models are very close to actual ship performance. Figure 21 illustrates this.

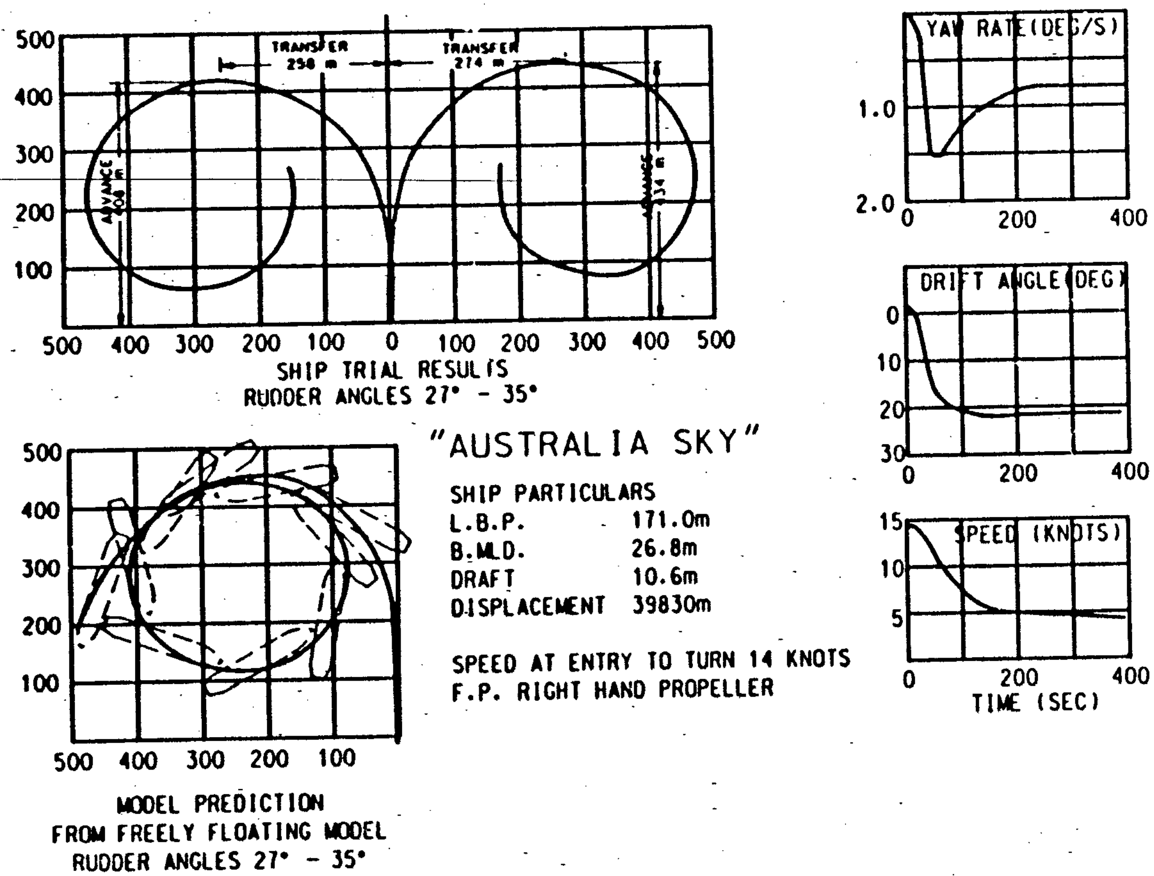


Figure 21. Turning Circles Vessel With Twin High Lift Rudders

Figure 22 shows model predictions for the twin high lift rudder system with the use of a joystick controller to give larger rudder angles. Ship trials confirmed the accuracy of this prediction for the M/V "Australia Sky".

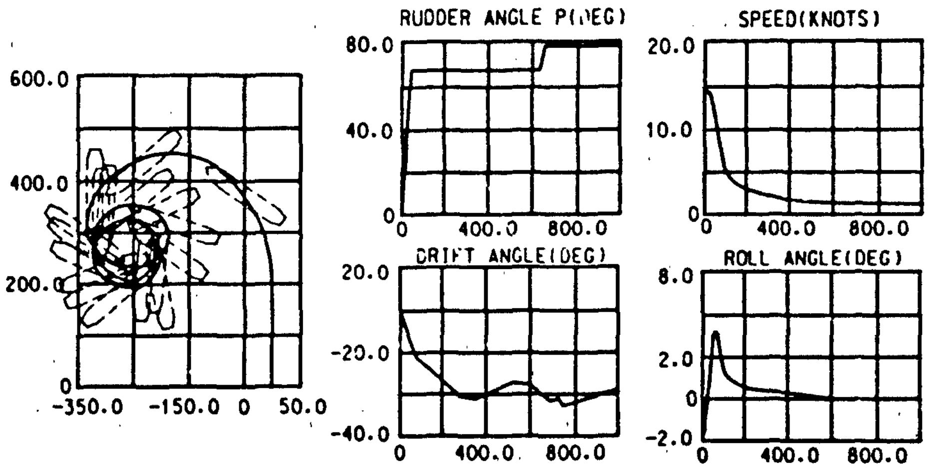
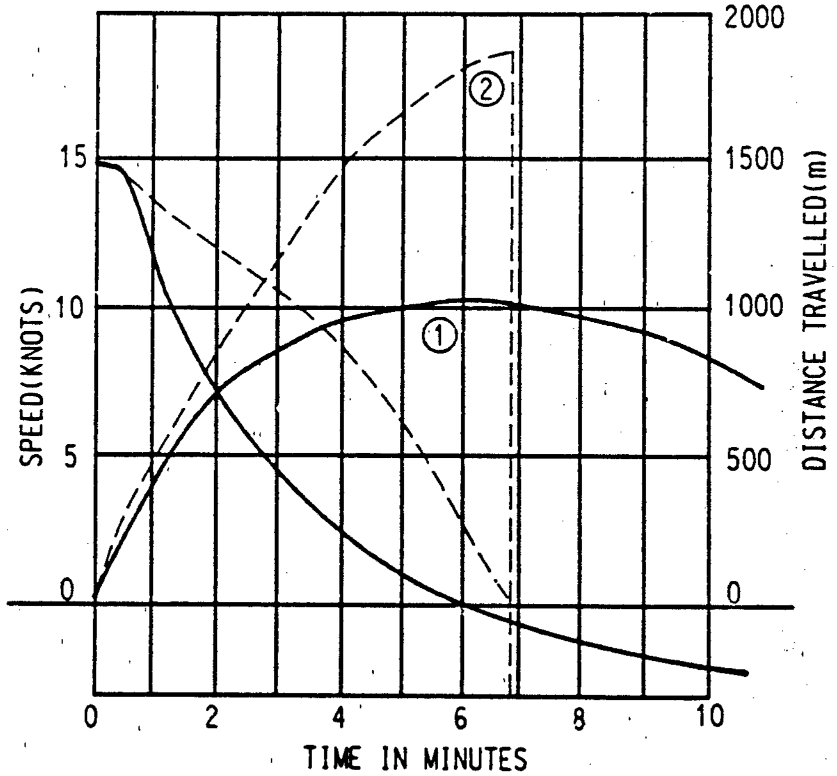


Figure 22. Model Predictions For Twin High Lift Rudders
M/V "Australia Sky"

Figure 23 illustrates the difference in stopping distance between an emergency stop by reversing the propeller in the normal way and by using twin high lift rudders in the "clamshell" position with the propeller kept running ahead. A point worthy of note is that, in the "clamshell" mode, the ship's heading is under full control at all times.



① In "Clamshell" Mode with Propeller Running "Ahead" Vessel Stops in 6 min 2 sec with a Sailing Distance of 1039m.

② With Propeller Running Astern And Rudders Amidship Vessel Stops in 6 min 39 sec with a Sailing Distance of 1862m.

Figure 23. Stopping Distance With Twin High Lift Rudders. Source - Trial Report of 171 M Tanker In Ballast Condition. Displacement 21,800 Tonnes

Figure 24 illustrates the ability to rotate "on the spot" using the twin high lift rudders and the bow thruster.

The joystick control system for a standard, independently operable, twin high lift rudder system, arranged for a dynamic positioning situation, is shown in Figure 25.

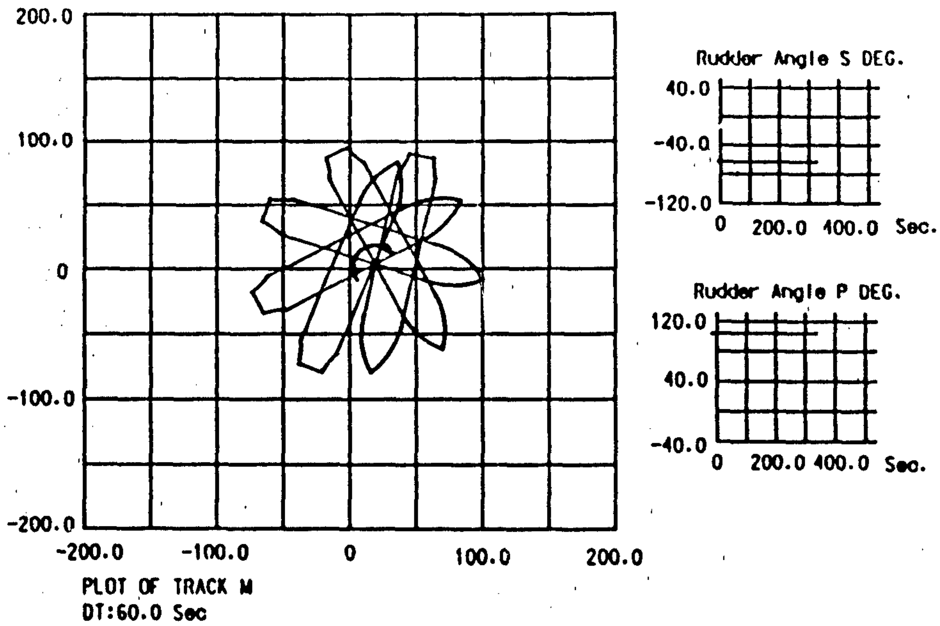


Figure 24. Ship Rotation With Twin High Lift Rudders and Propeller RPM For 8 Knots - Bow Thruster To Give 18 Tonnes

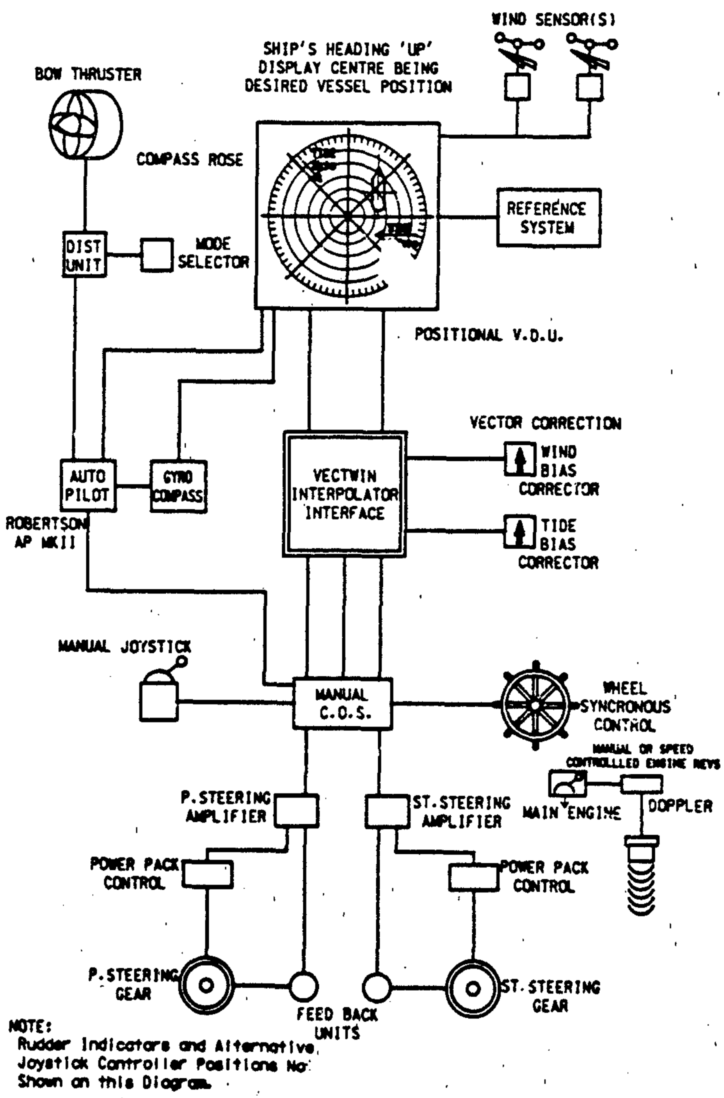


Figure 25. Basic Twin High Lift Rudders Auto D.P. Control (Typical)

9. CONCLUSIONS

After 15 years of experience on hundreds of ships of all types, the superior performance of the single and twin fixed geometry high lift rudder systems has been established. Their one piece construction has removed any concern regarding the suitability of these rudder systems on any vessel of any size, single or twin screw.

A major impediment to the introduction and acceptance of these rudders, particularly on ocean going vessels up the tonnage scale, has been the prediction of increased drag from some model test facilities. Actual full scale results on a statistically significant number and variety of vessels have conclusively shown these predictions to be incorrect and that a propulsion efficiency similar to the use of a single conventional rudder should be expected.

The benefits to be gained in many different areas are a compelling reason to consider high performance rudders for any new building, as well as for retrofit when maneuvering performance has not been satisfactory or when the safety or earning capability of a vessel can be improved. Experience has proven that high lift rudders will result in tighter turning circles, the ability to "turn on the spot" and "crab" sidewards, with the assistance of a bow thruster, and the ability to stop in a shorter distance without reversing the propeller. In addition, and unique to the fixed geometry high lift rudder, yaw is reduced and coursekeeping and astern performance improved.

The use of high maneuverability rudders, particularly the twin high lift rudder system, is truly a concept whose time has come. When all trade-offs are considered, it is also a concept which need not significantly increase the acquisition cost of a vessel, if specified early in the planning stage. In fact, it will, in many cases, reduce capital costs when compared with other systems for obtaining even close to the equivalent maneuverability.

REFERENCES:

(1) Saunders, H.E., "Hydrodynamics in Ship Design" , SNAME, 1957, Section 74.10, P. 723.

(2) Comstock, J.P., "Principles of Naval Architecture", SNAME, 1967, P. 510.

A LINGUISTIC SELF-ORGANISING CONTROLLER FOR RUDDER INDUCED WARSHIP ROLL STABILISATION

by Robert Sutton
Royal Naval Engineering College
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Sea Systems Controllerate

1. ABSTRACT

This paper gives consideration to the problem of suppressing rudder induced roll motion in a warship using a linguistic self-organising controller (SOC). A description of the SOC architecture is given and results are presented of computer simulations which show it to have a wide operational range. In addition, a detailed analysis of the robustness of the SOC to large variations in the parameters of the warship model is also reported. For comparison purposes, the performance of the SOC is matched with that of a fuzzy controller which has a fixed rule-base.

2. INTRODUCTION

Owing to the design configuration of certain modern Royal Navy warships, severe interaction or cross-coupling between the control surfaces and controlled outputs is an unwanted by-product. Of particular concern is the roll motion induced in such warships as a result of rudder demands during turning manoeuvres. Surprisingly, the control strategy currently being employed for warship manoeuvring does not attempt to account for any interactive behaviour. As a result, the operational efficiency of these warships can be adversely affected if the induced roll is excessive. Thus, the ability to maintain a more stable platform during the execution of manoeuvres would be most advantageous.

In an attempt to overcome this cross-coupling problem, a control strategy has been proposed based on a linear multivariable theory approach (1). Full-scale sea trials of the technique (2) have been undertaken and results have proved to be encouraging. The trials also highlighted, however, the necessity of having an accurate mathematical model of the ship being controlled for the approach to be completely successful.

By using fuzzy set theory the reliance on an accurate mathematical ship model can be circumvented and the system designer can heuristically develop a

linguistic rule-based algorithm from his or her knowledge of the plant and the desired control objective. Such an approach has been adopted (3) and a fuzzy rule-based controller for warship stabilisation developed. Simulation results showed the performance and robustness of the fuzzy controller to be better than that achieved using the multivariable approach. For the fuzzy controller to be effective over a wide operational range, it was found necessary for the controller to have multiple output fuzzy set options. To overcome the handicap of having these set options, it was concluded that a self-organising fuzzy controller may be more appropriate for the task.

In this paper, the application of a self-organising fuzzy controller proposed by Sugiyama (4) to the problem of rudder induced warship roll motion is discussed. It is noteworthy that in a recent survey paper (5) the application of such self-organising techniques to real problems is advocated. Although the paper assumes a basic familiarity with fuzzy set theory, some fuzzy set operations particularly relevant to this type of controller are given in Appendix A: the reader is referred to the tutorial paper by Sutton and Towill (6) for an introduction to the topic.

3. WARSHIP DYNAMICS

Using curve fitting techniques on time and frequency response data collected during full-scale sea trials, Whalley and Westcott (7) developed a three input, three output model of the non-linear manoeuvring dynamics of a Royal Navy warship. The model produces outputs of roll, yaw and forward speed in response to inputs of stabiliser fin position, rudder demand and propulsion power. In further work by Roberts et al (2) a reduced model derived from the work of Whalley and Westcott (7) is presented which relates fin and rudder inputs to roll and yaw outputs only. A modified version of this reduced model is used in the study discussed herein.

A block diagram of the complete simulation model used in this study is shown in Figure 1, where the rudder to roll interaction transfer function is denoted by $g_{12}(s)$.

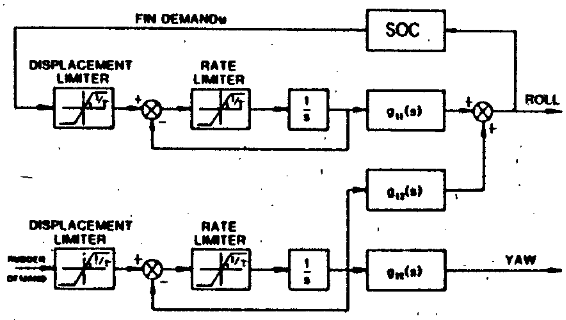

Figure 1. Warship roll stabilisation model

The interaction between the rudder and roll increasing in severity as the speed of the ship increases. Details of the individual transfer function elements are given in Table 1.

Table 1. Transfer function elements of the warship model

$$g_{11}(s) = \frac{k_{11}}{1 + 0.24s + 4s^2}$$

$$g_{12}(s) = \frac{k_{12}(1 - 8.57s)}{1 + 9.52s + 17.17s^2 + 53.3s^3}$$

$$g_{22}(s) = \frac{k_{22}}{s(1 + 11.2s + 32.25s^2 + 12s^3)}$$

It will readily be noted that the rudder to roll interaction transfer function $g_{12}(s)$ has non-minimum phase characteristics as a result of the $(1 - 8.57s)$ term in its numerator. This explains the reason that when a rudder demand is applied to the warship, it will initially roll into the turn and then as progress through the turn continues this inward heel will reduce until finally a steady-state heel outwards is adopted. A fin to yaw cross-coupling is assumed zero owing to the hull design having two sets of fins positioned about the yaw axis in this particular class of warship.

The steady-state function elements are speed dependent and are shown in Table 2.

Table 2. Steady-state gain variations

	STEADY-STATE GAIN		
SPEED (Knots)	k_{11}	k_{12}	k_{22}
12	0.144	-0.18	0.01
18	0.18	-0.932	0.02
26	0.168	-0.94	0.021

From Figure 1, it will be observed that the system includes two servomechanisms each of which contain two limiters, one describing the control surface movement restrictions and the other representing the control surface rate limits. The

limiting values, expressed in percentage terms, for the respective control surfaces are shown in Table 3. Furthermore, the fins on this class of warship are angle limited at speeds above 22 kts. This angle limit is imposed to prevent structural damage to the fins resulting from the extreme loads at high ship's speed. Thus the fin angle for the ship travelling at 26 kts was limited to a maximum of 71%.

Table 3. Control surface limiting values

	DISPLACEMENT	RATE LIMIT	TIME CONSTANT τ(s)
RUDDER SERVO	± 100%	20%	0.5
FIN SERVO	± 100%	100%	0.1

Throughout this study all system inputs and outputs are expressed in percentage terms. Therefore, it should be noted that the warship transfer function elements have been suitably adjusted for reasons of compatibility.

4. OPERATION OF THE SELF-ORGANISING FUZZY CONTROLLER

A basic self-organising fuzzy controller (SOC) as proposed by Sugiyama (4) can be represented as shown in Figure 2. The controller structure depicted in the figure illustrates the fundamental features of the SOC developed in this study.

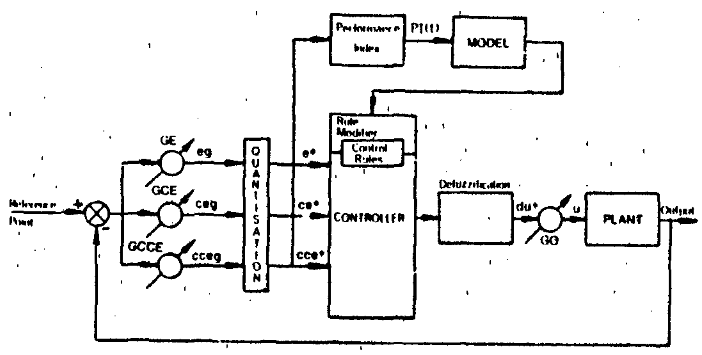

Figure 2. The basic structure of the self-organising fuzzy controller

4.1 Controller inputs

The plant output, in this case ship roll, is measured and fed back to the controller input, where it is sampled. The sampled signal is compared with the reference point which is zero to an error (e), a change in error (ce) and a change in change in error signal (cce).

These three error signals are then modified by the variable gain terms GE, GCE and GCCE to give error signals eg, ceg and cceg respectively, thus

$$eg = e \times GE \tag{1}$$

$$ceg = ce \times GCE \tag{2}$$

$$cceg = cce \times GCCE \tag{3}$$

Selection of the values of the gain terms has a significant effect on the performance of the controller.

4.2 Quantisation

The modified error (eg) and change in error (ceg) signals are then quantised. The quantisation process assigns appropriate integer values to the error signals to produce the signals e* and ce* which are used to fire the appropriate rules and performance matrix values and are derived by

$$e^* = (eg)_q \tag{4}$$

$$ce^* = (ceg)_q \tag{5}$$

where $(\ )_q$ denoted quantisation.

Early SOCs, such as that proposed by Procyk and Mamdani (8), simply assigned the nearest integer value in the range ±6 to the error signals. This tended to produce uneven controller action due to the step changes in controller inputs. To overcome the problems caused by step changes in controller input values, these signals are made to appear continuous by assigning weightings to the two closest integer values. This is achieved by using the relationship shown in equation (6).

$$w(i,j) = we(i) \times wce(j) \text{ for } \mu(i,j) \tag{6}$$

where w(i,j) : weight for w(i,j),
we(i) : weight for e* = i,
and wce(j) : weight for ce* = j.

4.3 Improved quantisation and data storage

a. Improved quantisation. With the use of seven linear quantisation levels (0 to 6), the performance of the controller is a compromise between steady-state performance and dynamic range. If the quantisation levels are made small enough to give fin control of small steady-state errors then the

dynamic range of the controller will not be large enough to give rapid control of large errors. It has been suggested that there are two possible solutions to this problem:

(1) Increase the number of quantisation levels. So that, firstly, the quantisation intervals are small enough to give fine control, and secondly, the overall quantisation range is large enough to give rapid control action for large errors. This would be expensive both in computer storage and time. It would also introduce extra complexity into the performance index.

(2) Instead of the linear quantisation levels (0 to 6) use non-linear quantisation. Non-linear quantisation assigns non-linear values to the quantisation levels (Qe(0 to 6), Qce(0 to 6)) so that the values chosen give small quantisation intervals near the reference point for fine control and large quantisation intervals away from the reference point in order to give rapid response to large errors. The quantisation levels used in this study can be found in equation(7).

$$Qe = Qce = (0,1.0,2.6,5.2,9.3,15.8,100) \qquad (7)$$

b. Data storage. The quantised error values and appropriate weighting factors are firstly stored for use in the rule modification process and then fed to the performance index and the controller.

4.4 Performance index

The performance index (PI) measures the relative performance of the controller and modifies the control rules to compensate for poor performance. Rule modification is carried out by the non-zero elements of the PI matrix. When the plant behaviour is out of track with the reference model, as given by the zero elements in the matrix, the magnitude of the non-zero elements specify the magnitude of the rule modification. By changing the size of the non-zero elements and the position of the zero elements, the reference model is altered. The size of the zero band is a compromise between the ease of learning and convergence of the rule base, and tight model specification.

Design of the PI is based on the system designer's perceptions concerning the required control action for any combination of error conditions. Both Procyk and Mamdani (8), and Sugiyama (4) argue that for the forementioned reason, the PI is not specific to the plant being controlled. Thus it is quite acceptable to select a proven PI. Hence, the PI used in this study is the same as that proposed by Sugiyama and is shown in Table 4.

The PI shown below is based on linear quantisation. Since non-linear quantisation is used in this study then the PI must be rescaled as the quantisation levels are now different from their real values. For example, with linear quantisation e* = 5 means that eg = 5, but if the quantisation levels of equation (7) are used then eg = 15.8.

Table 4. Linear controller performance index

		ce*												
		-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
e*	-6	-11	-10	-9	-8	-7	-6	-6	-4	-2.5	-1	-0.2	0	0
	-5	-10	-9	-8	-7	-6	-5	-4	-3	-1.5	-0.5	0	0	0
	-4	-9	-8	-7	-6	-5	-4	-3	-2	-0.8	0	0	0	0.2
	-3	-8	-7	-6	-5	-4	-3	-2	-1	0	0	0	0.5	1.3
	-2	-7	-6	-5	-4	-3	-2	-1	-0.2	0	0	0.8	0.5	1.3
	-1	-6.5	-5	-4	-3	-2	-1	-0.5	0	0.5	1	2	3	4
	0	-6	-4	-3	-2	-1	-0.2	0	0.5	1	2	3	4	6
	1	-4	-3	-2	-1	-0.2	0	0.5	1	2	3	4	5	6.5
	2	-2.5	-1.5	-0.8	0	0	0.2	1	2	3	4	5	6	7
	3	-1.3	-0.5	0	0	0	1	2	3	4	5	6	7	8
	4	-0.2	0	0	0	0.8	2	3	4	5	6	7	8	9
	5	0	0	0	0.5	1.5	3	4	5	6	7	8	9	10
	6	0	0	0.2	1	2.5	4	6	6	7	8	9	10	11

To compensate for this change in meaning the corresponding PI value is enlarged in proportion to the non-linearity of the quantisation. For example, if the element of Table 4 for e* = 5 is 6 then the corresponding element of the modified PI would be

$$6 \times Qe(5)/5 = 6 \times 15.8/5 = 19.0 \tag{8}$$

Scaling is carried out within the program to allow the PI and quantisation levels to be changed independently.

The performance of the learning algorithm is improved by making it continuous by taking the weighted sum of elements of the PI matrix as shown in equation (9):

$$PI(t) = \sum_{i=[eg]}^{[eg+1]} \sum_{j=[ceg]}^{[ceg+1]} (PI(i,j) \times w(i,j)) \tag{9}$$

4.5 Controller model

In the case of a multi-input, multi-output controller, a model is required if there is any cross-coupling between the inputs and outputs. Daley and Gill(9) propose that the model matrix should be calculated from the plant dynamics. However, this presupposes a detailed knowledge of the system. It has been argued (4)(8) that the learning nature of a SOC will compensate for an imprecise model matrix. Therefore, the elements of the model matrix only need to be of the correct sign as in this study.

4.6 Rule modification

The rule modification which takes place depends upon the output of the PI. Before the rules can be modified it is necessary to determine which rule was responsible for the good or bad performance at the sample instant. This is done by assigning a value to the delay in reward (DEL). Let DEL=n, then:

$$R(i,j)(t-nT) = du^*(t-nT) + w(i,j)(t-nT) \times PI(t) \qquad (10)$$

where $R(i,j)(t-nT)$ = rule for $e^*=i$ and $ce^*=j$ at $(t-nT)$, $du^*(t-nT)$ = constant output at time $(t-nT)$, $w(i,j)(t-nT)$ = weighting for $e^*=i$ and $ce^*=j$ at $(t-nT)$, T = sampling period, and $PI(t)$ = performance measure.

The introduction of continuous rule modification tends to make the learning too distributed. Therefore, a threshold level is included below which rule modifications are ignored. The effect of this threshold is that the distribution of the learning is reduced and normalisation of the rules around the maximum weighting assures the learning is not too weak.

4.7 Improved learning

Use of the PI alone to modify the control rules had been found to lead to incorrect rules being developed in some cases. By using heuristic knowledge of the necessary type of control action required to produce a good system performance, Sugiyama formulated certain "over rules". These "over rules" add an extra level of rule-based control over the self-organising mechanism and are listed below:

(1) Let the rule at $e^*=0$, $ce^*=0(R(0,0))=0$, since no change in controller position is required at the equilibrium state.

(2) Rules modified within the zone of influence of $e^*=ce^*=0(R(0,0))$ should be symmetrical with respect to $R(0,0)$, which leads to $R(i,j)=-R(-i,-j)$. This rule aids convergence to the reference point by ensuring that the total controller action for the zone of influence of $R(0,0)$ is always zero.

(3) When error (e^*) and change in error (ce^*) both are positive (or negative) then the corresponding rules should also be positive (or negative). This ensures that the control rules always act to reduce error.

4.8 Control rules

The control rules build up to form the rule matrix which initially contains no rules. Use of the third error term, change in change in error, improves the performance of the controller. Full implementation of a three dimensional (3-D) controller introduces unnecessary complication. In practice, it has been found that partial implementation of the 3-D but maintaining the two dimensional (2-D) structure of the controller produces very good results. Thus, the third variable, cce, is used to modify the 2-D PI and 2-D control rules as follows:

$$PI(t)_{3-D} = PI(t)_{2-D} + cce^* \tag{11}$$

$$Output(du^*) = Output\ (du^*)_{2-D} + cce^* \tag{12}$$

4.9 Zone of influence

The zone of influence is described in Appendix A. To simplify and speed calculation, rules with membership values below a threshold level, in this case 0.3, are ignored as they will have limited effect on the final controller output.

4.10 Controller output

The calculation of deterministic controller output is performed using the centre of area method. The controller output (du*) is multiplied by the output gain GO and the change in change in error compensation is added to give the change in fin demand required:

$$\text{Change in fin demand } (du) = du^* \times GO + cce^* \tag{13}$$

$$\text{Fin demand } (u(t)) = u(t-T) + du \tag{14}$$

The fin demand is fed into the fin dynamic model to produce a roll compensation. The resultant roll is then fed back to the input of the controller to close the loop.

5. SIMULATION RESULTS

All the results derived and presented in this work were obtained from simulation studies conducted on a Control Data Cyber 180/840 mainframe digital computer using a FORTRAN 77 compiler and GINO-F two dimensional graphics routines running under a virtual environment (VE) system.

Most of the results to be presented are shown on a comparative basis. The performance of the SOC being compared with that of the fuzzy rule-based controller reported in (3).

5.1 Gain and control variables

Initially, using a fixed ship speed of 12 kts and a rudder demand of 50%, a series of iterative computer simulations were undertaken. Each simulation run was examined in terms of average roll, mean square roll, and maximum and minimum roll angles, along with control effort measures, in an attempt to discover the optimum settings for the gain and controller variables.

The eventual variable values selected were a compromise to give an acceptable performance over the whole operating range. These values were

GE = 1.0, GCE = 1.0, GCCE = 7.0, GO = 4.0, DEL = 2, MDEL = 0.75, and T = 0.2 s.

It will be noted that a variable known as the reward weight (MDEL) is listed above in addition to those discussed in Section 4. The purpose of this variable is to weight the rule change corresponding to the delay in reward (DEL). In this study, a shaped reward function was used which assigns the maximum reward to a single sample and a reduced reward to samples on either side.

The response of the SOC to a rudder demand of 50% whilst the ship is travelling at 12 kts is shown in Figure 3.

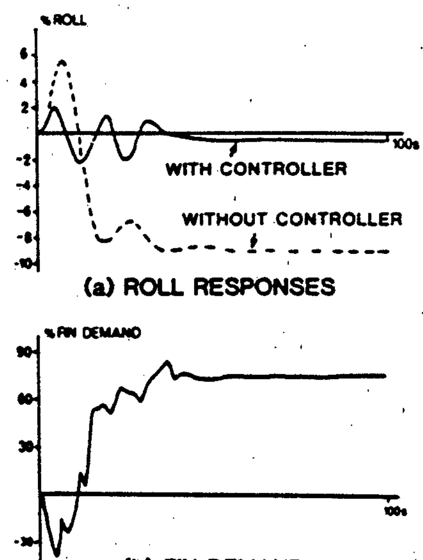

Figure 3. Roll responses and fin demand for a ship's speed of 12 kts and 50% rudder demand

5.2 Rule build-up trials

The SQC was tested with sequences of rudder demands and instead of clearing the rule matrix at the start of each new run, as is the case for all other trials, the rules were allowed to build up from one to the next. These tests were designed to show that the SOC performance remained good as rule build up progressed and that the rule modification procedure could start with a set of rules developed for completely different conditions and modify them to produce an acceptable response. In general, it was found that the change in roll reduction varied only by ±5% from the nominal.

5.3 Controller performance

The performance of both the SOC and the rule-based controller was measured by the amount of roll reduction each achieved. The roll reduction (γ) expressed in percentage terms being given by

$$\gamma\% = \left[1 - \frac{\text{Roll}_{RMS} \text{ (with controller)}}{\text{Roll}_{RMS} \text{ (without controller)}} \right] \times 100\% \qquad (15)$$

In addition, the simulation runs were also examined to ensure that a good roll reduction was not being achieved by employing unacceptable controller action.

The roll reduction performance for the two controllers operating at 12, 18 and 26 kts with rudder demands of 25, 50, 75 and 100% are shown in Figure 4. (It should be remembered that at 26 kts, the fin demand was restricted to 71%, as previously discussed).

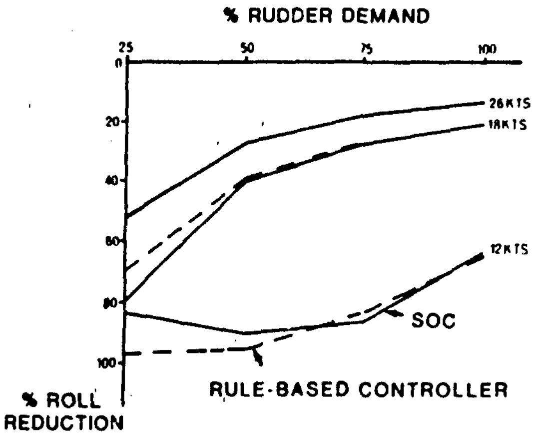

Figure 4. Roll reduction performance

At 12 kts, the SOC performance is marginally worse than that of rule-based controller for low rudder demands. However, as rudder demand increases, and with it roll severity, the performance of both controllers are very similar. At 18 kts, the SOC produces better roll reductions overall and at 26 kts the reductions are the same.

5.4 Rudder demand changes

A series of tests were conducted in which the controllers were required to cope with a reduction in rudder demand half way through a simulation run. Such a study was considered necessary to gauge the behaviour of the controllers to realistic rudder demand sequences which may occur during course changes.

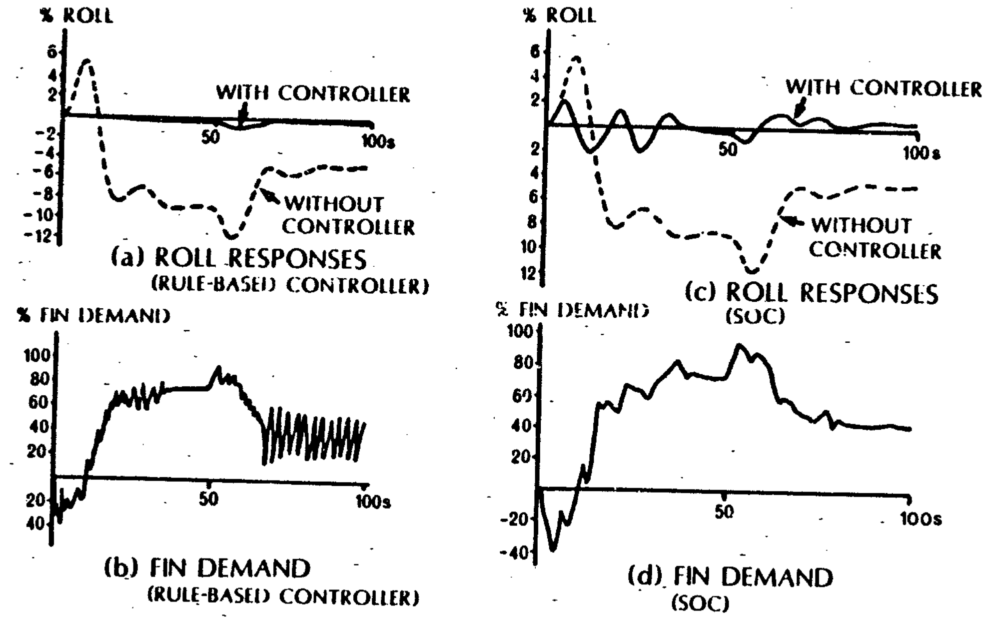

Figure 5. Roll responses and fin demands for a ship's speed of 12 kts and rudder demand changes from 50% to 25%.

Figure 5 shows the performance of both controllers for an initial rudder demand of 50% reducing to 25% after 50s whilst the ship travels at 12 kts. It can be seen quite clearly that the SOC is able to cope better with the changes by quickly reaching a steady-state fin position while the rule-based controller hunts violently.

5.5 Robustness

To prove that the SOC was able to cope with differing ship models, 15 individual model parameter changes in total were made to the rudder to roll transfer function $g_{12}(s)$ and the fin stabiliser to roll transfer function $g_{11}(s)$. The effectiveness of the SOC was considered at 12, 18 and 26 kts with rudder demands of 25, 50, 75 and 100%. For comparison purposes the rule-based controller was also tested under the same conditions.

a. Changes to rudder to roll transfer function $g_{12}(s)$. From Table 1,

$$g_{12}(s) = \frac{k_{12}(1 - 8.57s)}{1 + 9.52s + 17.17s^2 + 53.3s^3} \tag{16}$$

which may be factorised to give

$$g_{12}(s) = \frac{0.154\, k_{12}(1 - 8.57s)}{(1 + 8.2s)(s^2 + 0.2s + 0.154)} \tag{17}$$

Equation (17) can be compared with

$$g(s) = \frac{k_1(1 + \tau_1 s)}{(1 + \tau_2 s)(s^2 + 2\zeta_1\omega_{n1}s + \omega_{n1}^2)} \tag{18}$$

By comparing coefficients in equations (17) and (18) then

$$\tau_1 = -8.57s,\ \tau_2 = 8.2s,\ \omega_{n1} = 0.39 \text{ rad } s^{-1} \text{ and } \zeta = 0.255.$$

The following model changes were made, each change being tested separately:

(1) Increase k_{12} by 20%

(2) Decrease k_{12} by 20%

(3) Increase τ_1 by 20%

(4) Decrease τ_1 by 20%

(5) Increase τ_2 by 20%

(6) Decrease τ_2 by 20%

(7) Increase ζ_1 by 20%

(8) Decrease ζ_1 by 20%

(9) Increase ω_{n1} by 20%

(10) Decrease ω_n by 20%

The effectiveness of each controller was determined by considering the percentage change in roll reduction ($d\gamma$) as defined by

$$d\gamma\% = \frac{\gamma_a - \gamma_n}{\gamma_n} \times 100\% \qquad (19)$$

where γ_n = nominal roll reduction and γ_a = actual roll reduction. In order to condense the results, the mean percentage change in roll reduction ($d\,\bar{\gamma}$) at each of the ship speeds for all the test rudder demands (25%, 50%, 75% and 100%) was calculated and used in Tables 5 and 6. Thus the performance of each controller to the parameter changes listed above are shown in Table 5.

Table 5. Summary of controller robustness to changes in $g_{12}(s)$

	MEAN CHANGE IN ROLL REDUCTION $(d\bar{\gamma})$%					
	SELF-ORGANISING CONTROLLER			FUZZY CONTROLLER		
SPEED (kts)	12	18	26	12	18	26
PARAMETER CHANGE						
1. k_{12} + 20%	-4.1	-10.1	-10.0	-6.0	-5.79	-13.1
2. k_{12} - 20%	3.91	13.1	11.0	5.55	8.47	-1.25
3. τ_1 + 20%	0.36	0.56	0.47	-0.11	0.58	0
4. τ_1 - 20%	0.36	-0.94	-0.71	-0.11	-4.47	0
5. τ_2 + 20%	0.72	0.94	0.71	0.11	1.36	2.05
6. τ_2 - 20%	-0.47	-1.12	-1.18	-0.57	-1.75	-1.64
7. ζ_1 + 20%	0	0	0	0.11	-3.70	1.03
8. ζ_1 - 20%	-0.36	-0.37	-0.24	-0.45	-0.19	-0.21
9. ω_{n1} + 20%	0.47	0.56	0.71	0	-1.17	0.21
10. ω_{n1} - 20%	0	-1.31	-0.95	0.68	-1.17	0.21

From the results in Table 5, it can be seen that the overall roll reduction produced by both the SOC and fuzzy controller is fairly insensitive to changes in the cross-coupling transfer function.

b. <u>Changes to fin stabiliser to roll transfer function $g_{11}(s)$</u>. Also from Table 1,

$$g_{11}(s) = \frac{k_{11}}{4s^2 + 0.24s + 1.0} \tag{20}$$

which may be rewritten as

$$g_{11}(s) = \frac{k_{11}/4}{s^2 + 0.06s + 0.25} \tag{21}$$

Comparing equation (21) with that of a standard second order transfer function (h(s))

$$h(s) = \frac{k_2 \omega^2_{n2}}{s^2 + 2\zeta_2\omega_{n2}s + \omega^2_{n2}} \tag{22}$$

Then, $\omega_{n2} = 0.5$ rad s^{-1} and $\zeta_2 = 0.06$.

Thus the following model parameter changes were made

(1) Increase k_{11} by 20%

(2) Decrease k_{11} by 20%

(3) Increase ζ_2 from 0.06 to 0.1

(4) Increase ω_{n2} by 20%

(5) Decrease ω_{n2} by 20%

The controllers' performance with these parameter changes are summarised in Table 6.

Table 6. Summary of controller robustness to changes in $g_{11}(s)$

	MEAN CHANGE IN ROLL REDUCTION ($d\bar{\gamma}$)%					
	SELF-ORGANISING CONTROLLER			FUZZY CONTROLLER		
SPEED (kts)	12	18	26	12	18	26
PARAMETER CHANGE						
1. k_{11} + 20%	5.33	11.23	10.17	4.43	10.89	11.70
2. k_{11} - 20%	-6.76	-12.17	-10.17	-7.95	-11.86	-11.09
3. Increase ζ to 0.1	0.47	0.56	0.71	0	0.58	1.02
4. ω_{n2} + 20%	-10.44	-17.6	-15.13	-11.12	-17.12	-16.22
5. ω_{n2} - 20%	9.61	23.97	28.37	-56.4 *	-24.54 *	-9.87 *

Note: * Roll amplified for 12 kt - 75% and 100 rudder, 18 kt - 25% rudder, and 26 kt - 25% rudder.

It can be seen in Table 6 that changes in the fin stabiliser to roll transfer function can adversely effect the overall roll reduction.

6. DISCUSSION AND CONCLUSIONS

The work in this paper has shown that the self-organising controller can be successfully used for rudder induced warship roll stabilisation. The performance of the SOC has been seen qualititatively to be as good as a fuzzy rule-based controller (3) and, by implication, better than that of a multivariable controller (2). Fin demands from the SOC are smoother than those from the rule-based controller which, therefore, gives advantages in terms of fin induced noise reductions and stabiliser bearing wear rates.

The SOC has been shown to be very robust and produces good roll reductions over a very wide parameter range. The changes in performance of the SOC were found to correspond closely to the changing effectiveness of the fins. This indicates that it performs as well as possible given the parameter changes. In addition, it was also found to remain stable under all operating conditions which was not the case for the rule-based controller.

Traditional frequency domain stability analysis of a SOC is extremely difficult to undertake owing to the controller structure. Therefore, a more qualitative approach to stability analysis must be taken. Use of the PI alone to modify the control rules was found to lead to incorrect rules being developed on occasions. By applying the "over rules", this problem was overcome and helped to ensure that only helpful rules were introduced into the rule matrix. The incorporation of these "over rules" is essential for controller stability and has the additional benefit of reducing the SOC sensitivity.

The learning/adaptive nature of the SOC demands a relatively high level of testing and tuning to demonstrate that it will remain stable and produce beneficial control behaviour under all likely operating conditions. The results presented here give confidence that the SOC will be able to satisfy the requirements to be part of a high integrity warship roll stabilisation system.

The simulation results presented in this study show the viability of using the described SOC for suppressing rudder induced roll motion in a modern warship. Overall, its performance and robustness are shown to be better than that of a fuzzy rule-based controller and, by implication, that developed using a multivariable approach.

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APPENDIX A

Fuzzy logic controllers operate by interpreting controller inputs in terms of fuzzy control rules. Each fuzzy rule (R_i) is of the form

R_i : IF error (e^*) is E_i

AND change in error (ce^*) is CE_i

THEN change in output (du^*) is U_i

A fuzzy set A of a universe of discourse U is characterised by a membership function $\mu_A(u)$, which assigns to each element $u \in U$ a number $\mu_A(u)$ in the interval 0 to 1 which represents the grade of membership in A.

The membership function of each rule for a given controller input is calculated by fuzzy implication. For example, if rule (R_i) is expressed as

R_i : IF e^* is E_i THEN output is U_i

Fuzzy implication is expressed as

$$R_i = E_i \times U_i \tag{A1}$$

where x donates fuzzy implication

and the membership function is

$$\mu_{R_i}(e, u) = f_i\ (\mu_{R_i}(e), \mu_{U_i}(u)) \tag{A2}$$

where f_i donates implication function.

The controller output is inferred from the input and the control rule by the compositional rule of inference.

$$U_i{}' = R_i \circ E^* \tag{A3}$$

where E^* : fuzzy set of the actual controller inpuc, o : composition, and $U_i{}'$: inferred controller output.

The method of implication and inference used in this study is that of the Max-Product Rule proposed by Yamazaki (19) where:

$$\text{Implication} : \mu_{R_i}(e, u) = \mu_{R_i}(e) \times \mu_{U_i}(u)$$

$$\text{Inference} : \mu_u(u) = \text{maxmax}\ (\mu_{E^*}(e^*) \times \mu_{R_i}(e^*, u))$$

The max-product rule is also used for union and intersection of fuzzy sets. An example of the fuzzy sets used in this study is shown at Figure A1.

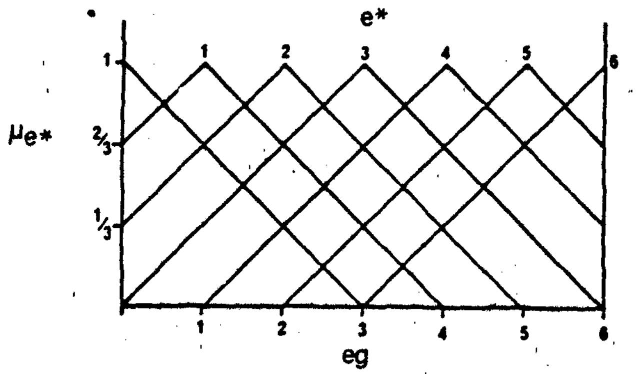

Figure A1. Fuzzy sets for error (e*)

Table A1, shows the non-zero membership values for $e^* = i$, $ce^* = j$ calculated using the max-product method. The non-zero values of membership function $\mu(i, j)$ defines the zone of influence of rule $R(i, j)$.

TABLE A1. Membership values for $\mu(i,j)(e^*=i,\ ce^*=j)$

		Change in Error (ce*)				
		j-2	j-1	j	j+1	j+2
Error (e*)	i-2	0.09	0.21	0.3	0.21	0.09
	i-1	0.22	0.49	0.7	0.49	0.21
	i	0.3	0.7	1.0	0.7	0.3
	i+1	0.21	0.49	0.7	0.49	0.21
	i+2	0.09	0.21	0.3	0.21	0.09

The zone of influence of R(i, j) is the zone where $\mu(i, j)$ is not equal to zero.

AUTOMATED SHIP SURVIVABILITY SYSTEMS

by CAPT Robert K. Barr, USN (Ret)
Ship Survivability Technologies

1. AUTOMATED SHIP SURVIVABILITY SYSTEMS

In recent years, the U.S. Navy has made many noteworthy advances in ship design, that complement the ability to meet new threats. The most notable of these are, the AEGIS Weapons System with vertical launched weapons which increases target management and weapons firing density, and the application of gas turbine engine technology which greatly reduces the weight and space required for propulsion. In each of these applications, the technology takes advantage of automation to achieve the desired results. The combined effects of these applications, while improving mission-effectiveness, also increases the demands on the remaining Hull Mechanical and Electrical (HM&E) systems within a given design. These systems could benefit from the application of increased, well coordinated, automation. The impact of this automation in the HM&E Systems, would reduce the time and personnel dependency required to correct casualties which would otherwise render a ship less than fully combat ready.

This paper discusses the application of a systems approach to the HM&E design requirements, which will facilitate, sound and reliable automation in support of increased reliability, hence survivability of warfighting capability. Included, are supporting design applications, such as, enclaving, redundancy and distributed systems to enhance the benefits gained from the applicable automation.

2. EXPECTATIONS OF AUTOMATED SURVIVABILITY SYSTEMS

The time, available technology and threat environment, coupled simultaneously with the increasing cost of manpower, and its reduced availability, dictates that we advance the application of coordinated, reliable automation into the hull, mechanical and electrical systems in future ship designs. This advancement would utilize a systems approach in management and analysis concepts, to determine how best to apply the available technology to provide the most affordable level of HM&E automation required to ensure constant availability of service support to a design's combat systems. The Measure of Effectiveness (MOE) expected from this

application, would be increased reliability of the entire ship as a warfighting unit. This MOE would be achieved by very rapid (near instantaneous) casualty correction, through use of automated remote controls to reroute services around the damaged portions of the systems. This degree of automation would reduce the number of personnel involved in the casualty correction and the time involved for those personnel to reach the damaged area and/or damage control points, within a given system.

2.1 Data flow and information gathering requirements

The heart of such an automated survivability system will be very dependent on gaining instant reliable information regarding the operational status of the various systems involved. This requires data collection by reliable sensors capable of determining temperatures, pressures, flow rates of water, air, hydraulic and electrical current mediums. These sensors must be capable of rapid detection and transmission of detected variations through sound lines of communication to centrally located standard Navy computers. These computers would be programmed to gather and analyze data in a manner that will provide the system operator information necessary to select a corrective action that, when employed, will effectively control any given HM&E casualty. The currently utilized AN/UYK-44 or its future replacement would be capable of the necessary programming to support this requirement. The control station design configuration necessary to support decision-makers would utilize the operator console concept enhanced through plasma displays that would provide visual representation of the system diagrams for all aspects of the HM&E design.

2.2 Readiness in depth

There have been many issues raised and resolved regarding how best to achieve *"readiness in depth"*. We may also consider the phrase *"force multiplier"* for application in this discussion. Relative to HM&E systems, the phrase that relates to both readiness in depth and force multiplier is the means to achieve designed-in "graceful degradation". Graceful degradation will best be achieved through a combination of design elements, starting with the automation of the HM&E system as the primary means of damage control in a hostile environment. This design approach will be further enhanced through enclaving the essential elements of HM&E including the management/control systems that will complement a distributed systems approach to HM&E support for combat systems readiness, including the computers involved in the automated management. The combination of enclaved distribution systems would support HM&E capabilities and provide the necessary redundancy to quantify a given degree of graceful mission degradation in any given hit environment that left an element of the weapons system intact. This would support maintenance of an acceptable degree of

sustained readiness in a hit scenario, thereby, enhancing the overall warfighting capability. Should a ship still be fighting following one or two hits, vice regressing to a mass conflagration situation to save rather than fight the ship, a force multiplication factor would have been achieved.

3. THREAT ELEMENT CONSIDERATIONS

There are considerations that must be taken into account when discussing a major shift in the ship design approach to management of the HM&E systems. The first consideration involves sensitivity to increased automation or maintenance of reliability in the man depending on the individual viewpoint. The Navy has experienced a few disappointments with some early major HM&E system automation, but recent years have shown an increased reliability and reliance on automation, particularly in weapons and propulsion systems. When a review of the control capabilities of the HM&E systems is undertaken relative to weapons systems over the past 40 years, we see many advances in weapons system automation, while there are few in the HM&E environment. In a few cases, some remote operation and redundancy has been deleted from late HM&E designs. Separated redundant elements of machinery have been dropped or consolidated in close proximity to other units increasing the potential for loss from primary weapons effects. There are other cases where the system provides more than one service, but lacks the capability to support all the services that maybe required in a combat environment. One such example is the fire main system. It is designed to provide firefighting water, then we added the countermeasures wash-down system, plus the care and feeding of secondary drainage system eductors and as a good measure, occasionally piped combat system and other auxiliary cooling water support from the fire main. The question arises regarding the capability of the system to support all these services simultaneously. The quick answer is the implementation of a priority system to cut out the lower priority requirements in favor of the higher. The next question is, who's action is required and when is that action taken. That answer is easy, the Damage Control Officer through his DCA following receipt of information that one or more of the required services is failing to be adequately provided. As one might consider, this would likely have a further detrimental affect on recovery actions. All of these design aspects impact the ability to effectively control the threat effects, which is necessary to achieve the previously stated goal.

3.1 Modern weapons speed and density

There is no question, sound experience was gained during WWII regarding ship design requirements and damage control doctrine, as relate to survivability. The kamikaze that flew into our ships then, can be compared to the air to surface missile of today. When

that is accomplished, it is easy to resolve a few differences that necessitate improvements in HM&E design. During WWII, many of our combatants were smaller, yet had crews ranging from 50% to 80% larger than those of today. The air to surface missile of today can go straight up at least four (4) times faster than the kamikaze could go straight down. The bomb carried by the WWII attacking aircraft had a devastating primary affect but little secondary affect while today's missile has, as a minimum, the equivalent primary affect coupled with a devastating secondary affect resulting from unexpended rocket fuel burning at very high temperatures. The threat weapons density and firing platform stand-off range of today are much greater, which dictates the constant maintenance of the capability to defend against multiple attacking weapons, even when hit. This requires quick recovery with fewer crew. Repair party personnel running about today's ship reporting damage and reacting to direction from repair party leaders and Damage Control Central as in WWII, will not react with sufficient speed to ensure maintenance of the combat systems through alternate system support.

3.2 Existing automation

Many design aspects of a postulated centrally controlled automated HM&E capability currently exist to varying degrees in different ship's designs. Having already discussed automation within the combat systems, it must be pointed out that the supporting electrical distribution systems of today have, though not centrally controlled, a significant degree of automation ensuring prioritization of electrical power distribution to the ship's combat capability. The 400HZ electrical power distribution provides for automatic splitting of generations to isolate damage or reduced reliability in generator units. The distribution systems are further supported by automatic bus transfers (ABT's) to ensure a shift to an alternate electrical power source in the event of a casualty. There are automated fire, smoke and flooding alarms, although few are supported by automated or remote operating systems to react to these alarms. There are automated chemical agent and radiation detectors for CBR defense capability. The newly designed Collective Protection Systems have automatic alarms related to maintenance of minimum over pressure including some remote control capability over ventilation fans.

The existing automated systems should be brought under the control of central management capability. That management would control other newly designed automated remote control systems to effect total HM&E automated management capability.

4. PROPOSED AUTOMATION

Consideration is provided in this proposal for the degree of

automated capability that now exists in combat systems and propulsion system design. The objective is to bring HM&E control up to the level existing in other ship's systems to the degree necessary to ensure an equivalent level of maintainability of readiness to bring about a quantifiable balanced improvement in warfighting sustainability.

The HM&E management and control capability must be achieved at a single control point, yet provided with an alternate control station with minimum essential capability in the event the primary station is disabled. The central control, alternate control stations and the control network would be provided a vital source of emergency electrical power with operator consoles also supported by emergency power-packs to ensure uninterrupted electrical power availability to the computers.

4.1 Design priorities

Primary design consideration must be provided to automation and management control of those services necessary to maintain the combat systems in the highest possible state of readiness.

a. Identified primary services. Includes the following:

Electrical power - Both 60HZ and 400HZ systems, to include the ability to support prior circuit prioritization related to a given warfare area with incorporated automatic load shedding in the event of reduced power availability.

Chilled water - Utilized for combat systems space and equipment air conditioning for maintenance purposes.

Cooling water - Necessary for maintenance of electronic components in the combat systems.

Compressed air - Required for system control switching, and operation of the ship's remote control system.

Ventilation management - To ensure a smoke and toxic-free atmosphere is maintained for combat systems and the system's operational personnel.

b. Necessary ship's system support services. Includes the following:

Buoyancy and stability maintenance - Ability of ballast systems and dewatering capability to support a stable weapons platform in a damaged environment. This capability will also contribute to overall ship safety and survivability where damage is extensive enough to result in a mass conflagration situation.

Fire main and fire pumps - Automated management - Since these functions routinely contribute to the overall ship systems operation and damage management in the event of fire and/or flooding.

Ventilation control of Collective Protection System (CPS) Which contributes to the overall operational safety and efficiency of all personnel in a CBR threat environment.

Smoke ejection system management - Of the ventilation system to ensure efficient removal of smoke and toxins in a firefighting scenario, including the potential necessity for circumventing a breached CBR citadel.

CBR detection system - Management which would provide rapid alarm warning, agent identification and to some extent, the degree of contamination and its general location dependent on the installed instrumentation.

c. Additional systems benefitting from automation - Automated firefighting system management for both manned and unmanned spaces could result in an indepth fire suppression capability in high impacting damage scenarios where personnel had to evacuate a space or the affected space is initially unmanned. This management control would be effective fore Halon, CO2 and sprinkler systems. In this system, the automated fire and smoke detection (sensors) system, now in the latter stage of development within the U. S. Navy, would be utilized. These sensors would complement the HM&E automated management capability.

4.2 Degrees of applied automation

Any discussion regarding increased automation is sure to provoke apprehension in both the design and operational communities regarding the degree of control allowed in the final design relative to the man-machine interface. In this consideration, the expectation is that an operator would always have the opportunity to affect system control. In every case, the system sensors and alarms should communicate with the computer system in a manner that would automatically notify the system operator of irregularities. That notification would be operator-acknowledged, hence silenced and then the casualty control procedure selected and manually initiated by the operator. The technology currently exists to gain a fully automated casualty control response for the HM&E automated management capability although there is a question regarding elements of desirability and affordability, both in funding and weight and space required for accomplishment. Future requirements relative to matching the modern threat would be achieved through the operator activated management control previously discussed.

5. SUPPORTING DESIGN CONSIDERATIONS

While the preceding discussion involves designing an increased management capability for the HM&E systems to enhance ship sustained warfighting capability there are additional elements of design that will further enhance the capability through mutually complementing each aspect of the design. In order to function, the automated HM&E management capability requires widely separated redundancy in all the effected systems including the application of a remote secondary management control station. In most current design requirements, redundancy is specified as a construction requirement which, in some cases, has resulted in achieving less than desired capability. There is no question that redundancy should be specified, but it could be a specific design rather than a specified construction requirement. The specified redundancy design considered most effective is that achieved through enclaving system service capabilities in multiple independent subdivisions throughout the hull. The incorporation of the CPS design in recent years has achieved enclaving to some extent, especially with fire zones and supporting ventilation systems, but failed to take full advantage of the concept relative to all HM&E systems. Many aspects of the enclaving design concept are in use and should be further implemented to provide true isolated system redundancy to all combat systems servicing HM&E capabilities.

Achieving redundant systems through the protection of enclaving also provides the basis for application of a distributed system design to further provide indepth survivability to service support elements. The distributed systems concept would provide control and unit linking throughout a particular service line in a manner that any or all enclaved redundant service support systems could service any part of a ship. In this design, damaged units that were no longer in commission would be isolated while remaining intact services would be rerouted to support system requirements. In the enclaved design the readiness indepth concept would be enhanced through use of redundant HM&E automated management control computers being enclaved and established management placed in a distributed systems design concept. This would provide depth in readiness that would effectively implement the element of graceful degradation.

6. TECHNOLOGY APPLICATIONS

The automation of ship survivability systems is intended to take advantage of existing technologies with the necessity for application only to achieve the objective. The key functions necessary have been previously discussed, but are resurfaced here to provide the opportunity to point out associated advantages to ship design through application of these technologies. This discussion will deal with specifics regarding sensors, remote

control capabilities and fiber optics application, all essential to improved HM&E system management.

6.1 Improved sensors

Through the use of miniaturized electronics,, weight and space requirements for many sensors have been reduced. This allows increased sensor application without penalty. The improved reliability and in many cases self-diagnostic, capability has reduced the maintenance requirements previously considered to outweigh the benefits of the sensors. Sensor are capable of accommodating many new detection requirements previously not available in miniaturized packages applicable to ship design. More reliable designs now exist for liquid level and pressure determination. Smoke, temperature, rate of rise and flame detectors now exist that utilize improved technology to increase reliability. Utilization of these technologies will increase available system status information while reducing reliance on personnel to determine a given status.

6.2 Remote control capabilities

In the automation of HM&E dependency on remote control capabilities will be increased to new heights heretofore not considered possible because weight and space involved relative to the density of application requirements to support the required capability. Today new designs provide increased reaction speed in light weight activators which have reduced friction and increased strength through applications of improved materials. Many of these activators are products of the space and aircraft design communities which have reliability and maintainability standards that are equal to or greater than those required for ship's design.

6.3 Fiber optics

The use of fiber optics will benefit the HM&E system management through reduced weight, space and increased data rate transmission over that of wire, while providing for increased reliability through added redundancy. Additional survivability benefits are gained through reduced flammability and electronics emissions interference including EMP and EMI. Reliability and maintainability of fiber optics are improved through both its ability for installation redundancy and ease in repairability. The application of fiber optics and the other previously discussed technologies in HM&E management will complement the design objective for improved warfighting sustainability.

7. CONCLUSION

Threat advances of today dictate the need for improved

management capability for combat systems servicing HM&E support in ship design. This is necessary to reduce the reaction time required to recover from any from of weapons effects damage. The technology recessary to improve management is available, although a total systems approach analysis is necessary to determine system design requirements. The proposed automated management capability will effectively increase warfighting sustainability, while simultaneously reducing reaction time and reliance on personnel to individually manipulate system controls. Early establishment of integrated automation in ship survivability design will permit the U. S. Navy to meet threats well into the 21st century.

IMCS ASSISTED DAMAGE CONTROL MANAGEMENT IN THE M-CLASS FRIGATE

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ABSTRACT

The Damage Control (DC) management needs a lot of information about the actual situation within the ship. All the separate bits of information need to be integrated into one complete (mental) picture, so that in case of calamities, the right decisions about effective overall countermeasures can be taken.

Up till now, the complete (mental) picture is created by transferring most of the information through the ship by voice communication and by pencilling in data on several ship's maps.

The use of a distributed VDU system allows information to be integrated centrally and that diminishes the risk of communication problems.

A special DC presentation system has been developed for the M-class frigate. This system is integrated into the IMCS (which contains a kind of distributed VDU system) and provides both automatic sensor status presentations and manual status input for the SCC as well as for the DC section stations.

1. INTRODUCTION

Recently, while completing the design of the functional capability of the Integrated Monitoring and Control System (IMCS) of the newly built M-class Frigates for the Royal Netherlands Navy (RNLN), Van Rietschoten & Houwens, in conjunction with the RNLN and the TNO/Institute for Perception, developed a new interactive presentation system which is specially designed to meet the needs of Damage Control management. This is one of the first operational

Visual Display Unit-based DC-presentation systems integrated into a ship's monitoring and control system.
The system is based on the automation of existing DC-operation procedures, [illegible] optimise a concept which has proven principally sound, but which has had some major disadvantages caused by imperfect provisions.
On central monitoring/control level, the IMCS has a three point distribution of interaction stations throughout the ship.

2. DAMAGE CONTROL

2.1. General

Naval vessels are designed to operate under wartime conditions and are supposed to be able to handle various degrees of hardships without fully losing their operational capabilities.
In general, their operational capabilities are threatened by fire (both in war- and in peacetime, due to their risky cargos, complex construction and distributed systems) and damage (also both in war- and in peacetime but, more likely, in wartime, due to hits).

The Damage Control organisation on board has the task to fight fires or damages so as to minimise the spreading of their effects and to diminish the operational consequences. The Damage Control organisation consists of local firefighting and damage-repair parties (DC-parties, usually operating from stations in the forward and aft sections of the ship), which are coordinated by a management team in the Ship's Control Centre (SCC) or NBCD headquarters.

In order to coordinate and assist the DC-parties in the ship's sections and to control the relevant ship's systems (such as ventilation and fire-fighting) effectively, the DC-management must be provided with proper information about the exact conditions in the various parts of the ship.

Up till now, analysis of actual incidents (Falkland experiences, Persian Gulf incidents) and of the majority of exercises carried out at e.g. the Portland training station of the Royal Navy (FOST, accessible to foreign navies as well) has nearly always shown that problems in communication, resulting in <u>incorrect or insufficient information</u>, are the basic cause of failures in coping with disasters properly.

It is this particular aspect of Damage Control (management) that needs special attention if one aims at a significant improvement of the DC-management provisions.

2.2 History

The way in which information is provided to the various places within naval vessels has hardly changed since the Second World War.

In earlier days, the information was passed on by messengers, supported by low fidelity voice-communication systems.
Later, the messengers were replaced by more reliable and extensive communication systems and voice communication carried most of the necessary information. In order to remember and visualise the various bits of information received, most of the relevant information-items were noted down or pencilled in on different kinds of ship's maps in section stations and headquarters.

When the time came that the ship's automation provided the use of special sensors for various purposes, it was only one step further to supply the SCC or NBCD headquarters (and usually only this place) with special ship's maps in which the various relevant sensor indications (fire, bilge-water, temperature) were shown. From these maps, sensor-information could be transferred by voice through communication networks to the DC-parties operating from the section stations. The situation-information, as it was observed by them, would be returned and pencilled in.

During the past years, the above mentioned information/communication systems have been refined, adding only minor improvements. Voice communication, even when sophisticated communication systems were applied, always remained the bottle-neck in which information could (and usually would!) be distorted or lost.

3. THE IMCS OF THE M-CLASS FRIGATE

The design philosophy of the M-class frigate has resulted in a computer based Integrated Monitoring and Control System (IMCS).
This IMCS contains a number of Local Processing Units and Automatic Control Units that are positioned in the machinery spaces in the vicinity of equipment so that they can be controlled/monitored.
These units are connected with a Central Processing System on central level (the SCC).
Several workstations have access to this system (see figure 1 for the location):

- in the SCC:
  - three operator positions, each containing three Visual Display Units (VDU's), a trackball and a functional keyboard; the layout of these positions is visualised in figure 2;
  - two manager positions, each containing one VDU, a trackball and a functional keyboard;
- in the DC section stations forward and aft, each section position containing one VDU, a trackball and a functional keyboard;

• in the Command Information Centre (CIC) by means of a special VDU.

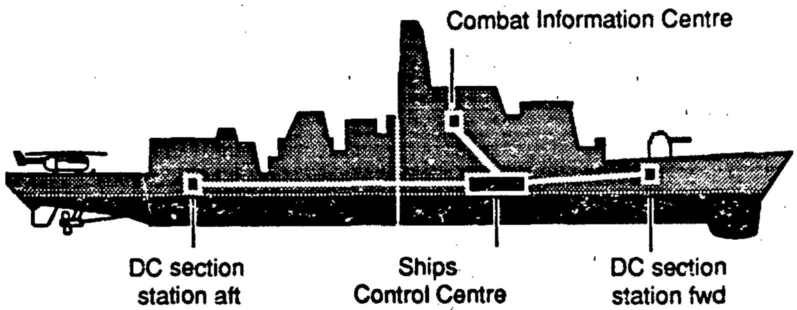

Figure 1. Location of the IMCS workstations.

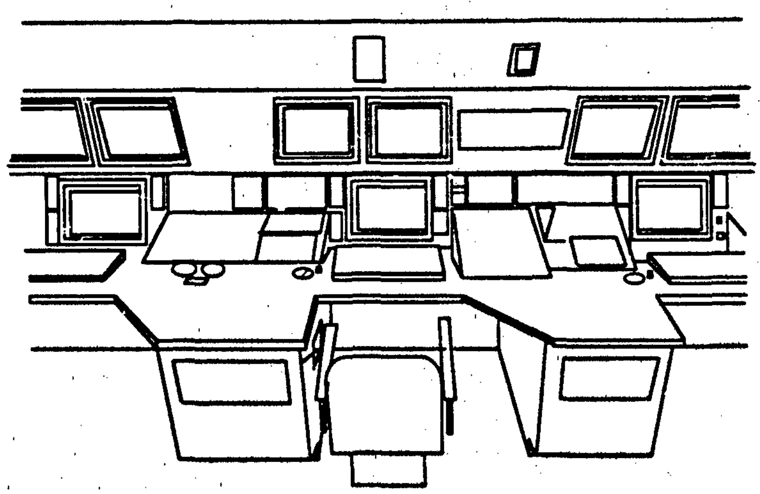

Figure 2. Layout of the SCC operator station.

The control and monitoring of the platform systems and the Damage Control is coordinated by these workstations. The operator positions allow direct control of installations, while the other positions only allow monitoring and interaction with IMCS management facilities.

Normally, only one of the operator positions is manned (one-man control of the whole platform from the SCC), but in higher

operational conditions, such as battle stations, all positions are manned.
Of these three operator positions, one is used for control of all electrical power generation, distribution as well as auxiliary installations, another position is used for propulsion control, while the third is used for NBCD control.
The manager positions are occupied by the Mechanical Engineering Officer and the Damage Control Officer. The latter manages all activities on board concerning Damage Control; the NBCD-operator carries out all control actions that concern NBCD related platform systems and he keeps in touch with the section stations by communicating through the VDU system and the dedicated communication lines.
The section stations are manned by the section leader and his assistants; they carry out the actual countermeasures against calamities (such as fire-fighting, damage repair, etc.) while being guided by the management team in the SCC (the NBCD-operator as well as the DC-officer).
The VDU in the CIC is positioned next to the Commander of the frigate and serves him as a source of information concerning the situation on the ship's platform.

The VDU presentations which are available at all workstations are:

- alarmtables, serving dedicated purposes in different modes; the alarmtable is the trigger to enter the system when an alarm occurs;
- mimics; these are special dedicated schematic presentations of platform installations used for control and monitoring;
- DC-plot presentations, used for DC-management;
- stability control presentations, used in relation with the IMCS Stability Control Module (see the concerning paper by R. Moerman and W.van Nes);
- other special presentations, like Trendpresentations, Assistpresentations etc.

The interaction with the IMCS takes place by using the trackball for selection of components on VDU presentations and by using the functional keyboard to give the commands (like controlling platform components or retrieving specific information or manipulating with information items).

4. DAMAGE CONTROL MANAGEMENT; HOW IT WORKS AND HOW TO IMPROVE IT

As indicated in chapter 2, DC-management means the coordination of all activities on board concerning DC-countermeasures. Principally, this management implies two important mechanisms:

- forming a (mental) picture of the actual situation within the ship, using both (quickly available) sensor information and situation observations by local personnel;
- using this mental picture in the decision-making process, resulting in decisions regarding overall countermeasures against calamities, such as:
  - to control relevant platform systems in such a way that they are adapted to the current circumstances: this can be a ventilation crash-stop or a killing of all installations that are in a burning compartment. This can be controlled by the NBCD-operator in the SCC using his workstation, or by personnel operating locally in the ship on his instigation;
  - to perform the necessary countermeasures against calamities: i.e. local firefighting, damage repair, taking care of casualties etc.; principally, this task has to be carried out by the DC-parties in the ship's sections on their own instigation, but if necessary (e.g. when the SCC has a better overall picture of the actual situation in the ship), on instigation of the SCC.

The first mechanism mentioned above, is usually the bottle-neck in the DC-management process due to the communication problems mentioned earlier. The second mechanism is consecutive to the first mechanism, which means that if the first goes wrong, it will have (devastating) effects on the second.
In principal, the second mechanism should not present many problems, provided that the SCC management crew is well trained and capable of their job: the presence of the workstations and the communication links for the NBCD-operator guarantees that all relevant and necessary facilities are there.

In order to cut down the problems concerning the first mechanism (collecting the right -mental- picture), one should ensure that correct information is provided in a suitable way. That means that the necessity of voice-communication (consuming a substantial part of precious operator's time as well as creating risks for information-distortion) should be reduced by a proper DC-management system that gives the DC-manager and the operators (both in the SCC as well as in the ship's sections) access to the right information. This information should present an accurate, integrated picture which is based on automatic sensor input and on manual input from the section stations or the SCC.
The manual input is very important: Damage Control is particularly important during calamities and the risk is great that, during calamities, sensors will not function correctly or not at all because of damage. Therefore, automation within Damage Control based upon sensor signals is not a feature to be sought after. That is why the sensors are normally used as a 'trigger alarm medium' and why,

during calamities, human observation plays a very important part. So, if one aims at creating a central information database, this implies that manual input facilities are required.

Of course, a system that is designed to be used by DC-personnel should be simple and straightforward, so that all personnel will be able to operate it under stress-conditions without making mistakes in interpretation and/or interaction.

In the optimal situation, this system should be combined with DC-platform system operating possibilities. It should also provide this very same information to the DC-parties operating locally in the ship's sections. The first requirement has already been achieved within the IMCS of the M-class frigate (the NBCD- and other operators can use their workstations for controlling the platform systems), the latter requirement will hopefully be achieved in the (near?) future.

5. PHILOSOPHY OF THE M-CLASS FRIGATE DC-PLOT PRESENTATION SYSTEM

5.1. Required contents of the system

As already indicated, one of the main reasons for the introduction of DC plot presentation on VDU's in the M-class frigate DC section stations, is the necessity to reduce voice communication between the SCC and the DC section stations. This can be accomplished by:

- integrating all relevant information for damage control in DC-plot presentations;
- enabling the DC section stations to use all other system presentations that can be of interest to the section station crew;
- providing the workstation in the DC section station with an alarm annunciator function, showing the relevant alarm information as a kind of pre-warning; this alarm annunciator is always shown, independent of the presentation shown at the (single) VDU of the section position. The NBCD-operator in the SCC remains responsible for the actions to be taken to deal with the alarm.

5.2. Implementational requirements

The DC-plot presentations may not increase the workload for the section station operator. Therefore, the necessity to switch between presentations has to be reduced as much as possible. If switching is needed, then the number of operator-actions has to be as small as possible and commands may not be complicated. The same holds for actions that require that situation-information to be entered into the system ("plotting").

The operator must be able to focus on the situation-information that requires his attention. To prevent him from being distracted by irrelevant data, the "all dark" principle has to be applied. This means that only the information that differs from the normal situation is presented to the operator. To enable the operator to consult all available information, it is possible to toggle between the "all dark" mode and the mode in which all information is presented in full detail.

The operator has to stay aware of the location of the (alarm)situation which is shown in the DC-plot presentation that is presented to him. This is realised by showing a small picture of the ship at the bottom of his VDU in which the location is highlighted. The operator is also guided by the 'zoom' mechanism.

To optimise the operator's assessment of the situation, he has to have the opportunity to interpret the situation that is presented to him in a DC-plot presentation as fast and as accurate as possible. This is realised by presenting almost all information by symbols and colours, whereas texts are hardly used as they need to be read and interpreted, which takes more time than understanding graphics.

The operator must be able to oversee the extent of problems in the ship. Therefore, next to the situation-information on which the operator focusses, the situation in adjoining locations has to be shown as well.

Because the DC-plot presentations are an integrated part of the IMCS, the Man Machine Interface of DC-plot presentations must be fully compatible with the Man Machine Interface of the rest of the IMCS.

The crew of the M-class frigates may have prior experience with other ships of the RNLN. If, in that case, the system of DC-plot presentations in the M-class frigates does not resemble the system used on other ships, then it would be possible that, in an emergency situation, the crew members would not recognise the presented information. Therefore, the adopted symbols and colours have to be comprehensible for the operator and the presentations have to resemble the existing presentations as much as possible.

6. CONSTRAINTS AND PROBLEMS ENCOUNTERED

Designing a new VDU-based information system for DC-management purposes implies that many constraints, caused by choice of hard- and software configurations, have to be taken into account.
If the system has to be built with MIL-spec equipment and has to be based on graphical presentations, these constraints will be even larger than in a normal system.

But before designing a proper system, one has to ask oneself the questions (as is usual when automating processes): what do I really need (in detail) for proper DC management and how do I need it? This question has to be answered in terms of:

- sort of information;
- concept of information-presentation;
- way of presentation (colours, symbols);
- way of interaction, if needed.

Basic constraints and problems encountered during the design phase for the M-class frigate were:

- hard/software-caused:
  - the size of the VDU's; a small screen hampers the graphic presentation of complex situations which are widely extended over inner parts of ships;
  - resolution of the VDU's; this, in combination with the distance between screen and eye, determines the minimum size of the adopted symbols;
  - graphic processor; rugged graphic processors are rare, and those available do not always provide the exact possibilities for presentations that are wanted;
- situation-caused:
  - a proper concept in which all above mentioned questions were answered, was not available at the start of the design phase;
  - the DC-management presentations have to be used next to and in combination with mimic presentations of all different platform systems. For these mimic presentations a complex and thoroughly designed principle had already been agreed on and this implied limitations and constraints on use of colours, symbol-forms and interaction procedures;
  - the principle of the Man-Machine Interface, in which the DC-presentation concept is used, had already been defined and this implied that an alarm status overview, presented on a dedicated VDU, acted as initial trigger for the operator and formed the starting point from which he "enters" the information system for both mimics and DC-presentations (a concept based on the "operation by exception" philosophy); also, a basic conversation dialogue had already been defined;
  - the available interaction provisions in the ship's section stations were defined;
  - interaction provisions were to be used wearing special gloves (anti-flash gear or NBC-clothing);
- human limitations:
  - in practice, operators can distinguish only a limited number of different colours and basic symbol forms; this implies that one cannot use as many different symbols as needed for all different information-types ;

- especially in stress situations, operators need more time to recognise alpha-numeric (textual) information than to recognise graphic information; this implies that a presentation concept has to be choosen that takes this into consideration.

7. GRAPHIC DC PLOT PRESENTATIONS

7.1. General

The DC-information presentation system that is designed by Van Rietschoten & Houwens, in conjunction with the Royal Netherlands Navy and the Dutch TNO/Institute for Perception, consists of a hierarchically orientated series of graphical presentations of the ship's interior. In this presentation concept, three levels of presentation are available so as to meet different needs:

- level 1: a general overview of the whole ship;
- level 2: overviews of the sections of the ship in a limited number of steps;
- level 3: a detailed view of all compartments and decks in many steps.

In figure 3 this presentation concept is graphically clarified .

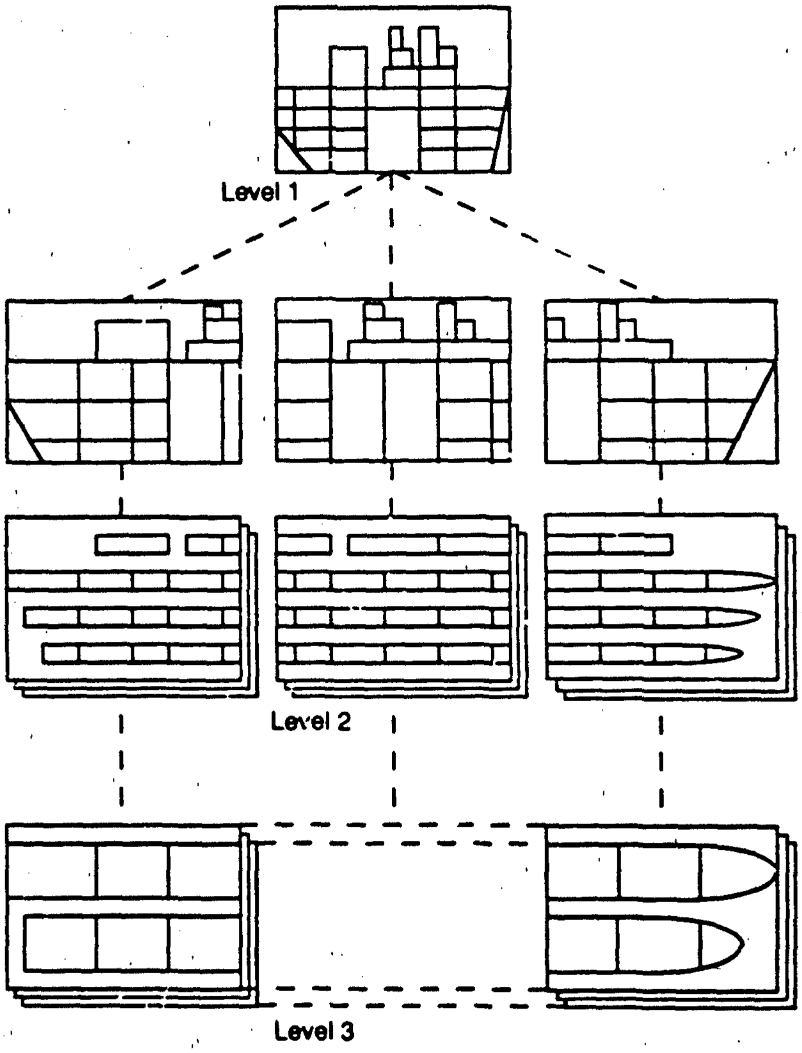

Figure 3. Hierarchical presentation concept for the DC-plot presentations showing the three levels.

These three levels serve different purposes:

- the general overview supplies a bird's eye view of the general situation in the ship to the DC-management in the SCC and is also used by the ship's command in the Command Information Centre (on the dedicated VDU);
- the sections' overviews are designed to relieve the task of coordination during major disasters that affect larger parts of the ship and both the SCC-operators and the section operators can use these presentations for this purpose. The presentations are divided into three groups: the forward, midship and aft part of the ship. Each group lists presentations of vertical and horizontal views of the concerning part. For these views, a scrolling mechanism is available. During normal operation of the ship, the presentations of the horizontal views of the forward and aft part of the ship also serve as a local fire-alarm "panel" (on the VDU's) for the sections themselves;
- the detailed compartment views serve as a working level for all operators as it gives all detailed information that is available during major and minor disasters. Here too, a scrolling mechanism is available.

The information presented by means of this concept can be divided into four different groups:

- layout of the ship's interior, containing related information about section, framenumbers, compartment-identification etc.; the layout is presented in such a way that it supports the orientation of the operator: this means that the most familiar features of the ship's interior, like corridors, stairs etc., are graphically highlighted. Also, this facilitates the coordination of the DC-parties, for whom transportation routes are essential.
- indication of the general situation in the ship or section, like crash-stop or ventilation, pre-wetting, electrical isolation etc;
- indication of the specific situation in a certain part or compartment, like fire, leakage, damage, casualties etc.; this information is presented by means of symbols in the presentation of the location itself;
- textual information, plotted by operators: information which cannot be (easily) transferrred by means of symbols.

The information mentioned above in the 2nd and 3rd point can be supplied by either platform sensors or by manual operator input (validations and new situation-information). This information is integrated by using a specially designed set of symbols. Standard symbol forms and colours related to the sort of information play an important role in this set.

7.2. Interaction

The interaction with DC plot presentations can be divided into three parts:

- the DC-plot presentation request: one wants to see a specific presentation;
- the DC-plot presentation information input: one wants to supply information into the system (like plotting the existence of holes in the hull);
- the operator requests information details: one requires information that is normally not shown on the presentation, but that is only available on special request.

a. The DC-plot presentation request

This request can be made from three starting points:

- the alarm table or mimic presentation: the operator can be alerted by a (NBCD) alarm which is presented on these presentations, in this case he can select the identification of the accompanying DC-plot presentation (further indicated as "DC-plot") using his trackball cursor and that results in the presentation of the level 3 DC-plot in question on one of his VDU's. The DC-plot will automatically be centered in such a way that the alarm is positioned to the center of the presentation as near as possible ;
- A DC-plot is already shown on a VDU, but the operator wants to see another level or area of the ship; in that case he can select the level or area he wants to see by using a special interaction scrolling feature which gives access to higher or lower levels (if possible) or to other areas within the same level (e.g. more forward, aft , higher or lower decks);
- the operator is working with a presentation which is not related to the DC-plots, but he wants to see a DC-plot for his next action. In this case he just has to enter the NBCD identification code of the compartment he is interested in and he will get the required DC-plot. If he does not know the specific identification code, he can enter the general "DC-plot" command which gives him access to level 1 and from there he can "zoom" into the presentation he wants.

b. DC-plot information input

Situation information can be added to the system ("plotted") by selecting the location about which special information is available or by selecting the sensor about which signal-detailed, validated information is available. After the selection, the operator can use

menus to enter his input, which can be a specific plotting symbol, text or other specific information.
The system offers the possibility to add extra information to symbols. Normally, this information is not shown at the DC-plot, but it can be retrieved by a separate, detailed presentation-request. Examples of this feature are: the exact number of casualties, the exact time a fire started, was attacked or was extinguished etc. If an operator does not add specific times to certain occasions (indicated by the plotting of symbols) the system automatically enters the time of plotting.

c. Operator request for details

If needed, the operator may request details about certain symbols in DC-plots. To do so, he simply selects the symbol in question by using his trackball cursor after which a two line presentation is shown to him at the bottom of his VDU presentation. This two line presentation contains all available details about the sensor or about the situation represented by the symbol.

7.3 Colours

Colours are used for characterisation of information in a hierarchical way.
The colours that are actually used, are based on a division into four main colour/information types, used for primary- and secondary information.

The primary information consists of current information (related to the very specific situation at a certain moment) for which generally the following code is applied:

- red: information indicating a (potential) dangerous situation which needs immediate operator action or attention;
- yellow: information which needs the operator's attention;
- green: information concerning normal conditions or situations;
- pale blue: information concerning countermeasures against calamities.

The secondary information consists of the static, passive background information and is characterised by a cognitively neutral presentation. Amongst the colours which are used for the secondary information there is a difference in luminance, which is used in three levels:

- white, as the highest luminance level, used for indicating the ship's layout;
- dark grey, as the lowest luminance level for the identification of transportation routes (both horizontally, corridors, and vertically, hatches and ducts).

- light grey, for the textual identification of compartments and for indicating the position of sensors in passive modes;

This colour division is fully adapted to the colour-code used in all other VDU-presentations (mimics, alarmscreen,etc.) and is, in general, in accordance with ISO-standards. The exact definition and luminance of the colours that have been chosen for the VDU's enhances a proper cognitive interaction between the operator and the VDU-information that is presented with the aid of this colour-coding. This means that information which is important for DC management (indicated in red and pale blue) is highlighted on the screen.

7.4 Symbols

The symbols that are used in the DC-plots are derived from the standard symbols that are currently used for the written reports in the ship's maps, as we indicated earlier. These symbols have been adapted to the use of raster scan, cathode ray tube VDU's in such a way that they fit in with the existing symbols for mimics and that they allow the use of a set of written symbols that bear a close resemblance to them for parallel reports (for back-up purposes).

Basically, there are six categories of symbols that can be recognised by their forms.
These six categories are:

- sensor symbols, consisting of a letter presented in inverse video in a square form; these symbols are the same as those that are used in mimics;
- door/hatch symbols, represented by a triangle and including an indication of the direction in which the door/hatch opens;
- fire symbols, represented by an equal sided triangle. Status information (like false alarm, fire under control/extinguished) can be added to the basic symbol;
- damage symbols, which represent the current situation (like a hole in the hull) in a simplified, graphical way;
- symbols indicating the presence of special equipment (breathing apparatus, pumps etc.), consisting of a capital letter (indicating the sort of apparatus) in normal video;
- symbols indicating the presence of dangerous goods (Ottofuel, oxygen), consisting of a diamond.

The colours used for these symbols in their various modes are based on the above mentioned colour code. Almost all information is presented in a cognitively redundant way, using size, form and colours.

In figure 4 some examples of the symbol forms, including colours, are shown.

high temperature sensor
red lines and letter when activated

hatch symbol
light grey to show position
fully red when in alarm

smoke/fire/fire attacked symbol
red line/red triangle/
red triangle and blank line

hole/tear symbol
red (when plotted)

PL

breating aparatus
(in Dutch:"PersLucht")
pale blue (when plotted)

ammunition
orange (when present as
static information
or when plotted)

Figure 4. Examples of symbol forms and their colours.

7.5. Contents of information presented

The source of the information that is presented in the DC-plots can be an operator (from the SCC as well as from the section stations), the system itself (automatic sensor indication) or a combination of both.

- An example of an information item produced by the operator is the plotting of the presence of a set of breathing apparatus in a certain location;
- An example of an information item produced by the system is the state of a hatch which, given the ordered closing condition, should be closed, but is not;

- An example of an information item which is the result of a combination of both is a smoke alarm: if a smoke indication sensor is activitated, then it might concern just some smoke from e.g. a cigarette or it might concern smoke from a smouldering fire: this means that every smoke alarm has to be validated before the alarm can give precise information about the current situation in the ship. This validation can only be given after (local) human observation. If a crew member reports that the smoke alarm is, in fact, not a real fire alarm, the operator can add this information to the DC-plot presentation by plotting a specific symbol (in this case an extension to the original smoke alarm symbol) to the alarm symbol.
  If, however, the crew reports that the alarm concerns a true fire indeed, then the operator adds the symbol that indicates "fire".
  The addition of symbols may change the colour of the final symbol in such a way that the new colour represents the character of the information presented.

Not all information is presented to the operator in symbols. Some information is presented in the form of thin, coloured lines, which indicate the area for which that information holds. In case of a ventilation crash-stop or pre-wetting, the lines are shown at the top of the presentation, and for a representation of the water level outside the hull (in relation to the deck-level shown) the lines are shown at both sides of the presentation.

In spite of all the above mentioned features, it is not possible to represent all information by symbols because one cannot create a symbol for every possible occurrence beforehand. Therefore, the system provides the possibility to add textual information which is presented between the decks in dedicated lines. In this way, any sort of information can be entered into the system.

8. EXAMPLES OF DC-PLOTS

In figure 5 and 6 two examples are shown of DC-plots of level 2 and 3. Compared to the normal presentation on a VDU with a black background, the plots shown are, of course, in inverse video. In these examples a situation is simulated in which a frigate has been hit on starboard side in the Forward Engine Room.

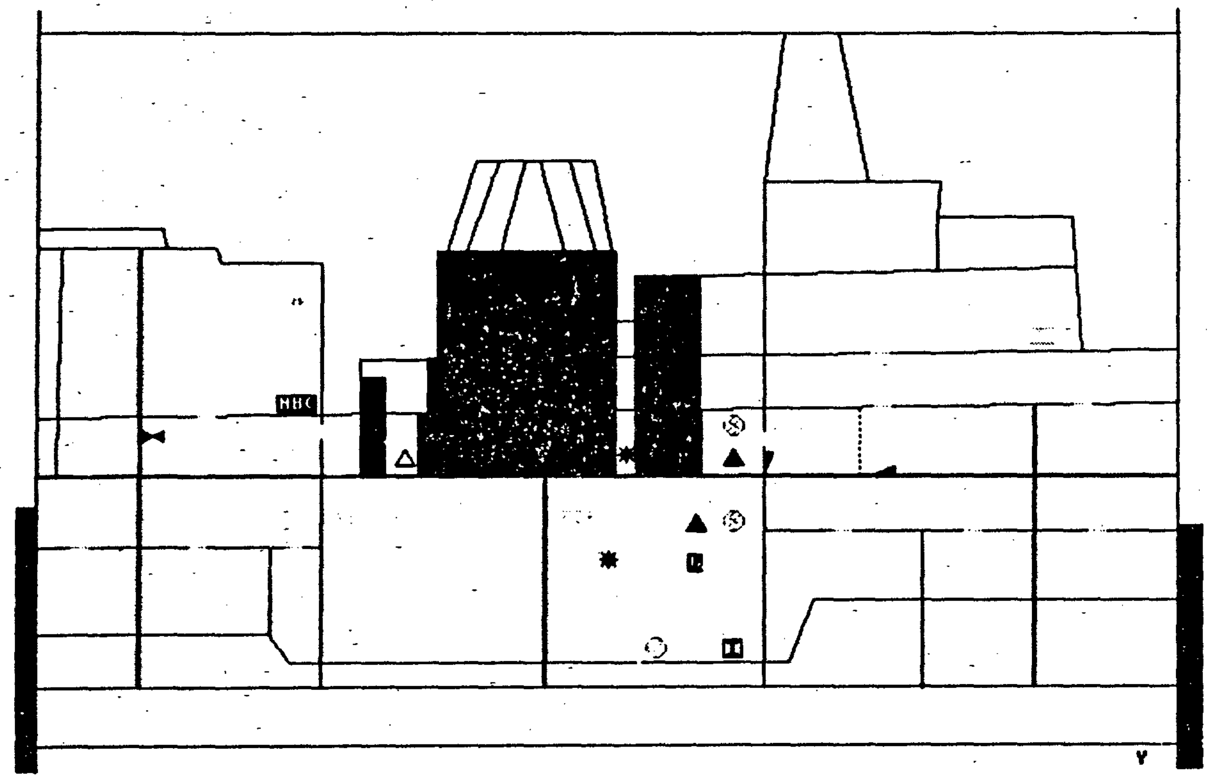

Figure 5. Level 2 DC-plot: horizontal view of midships section.

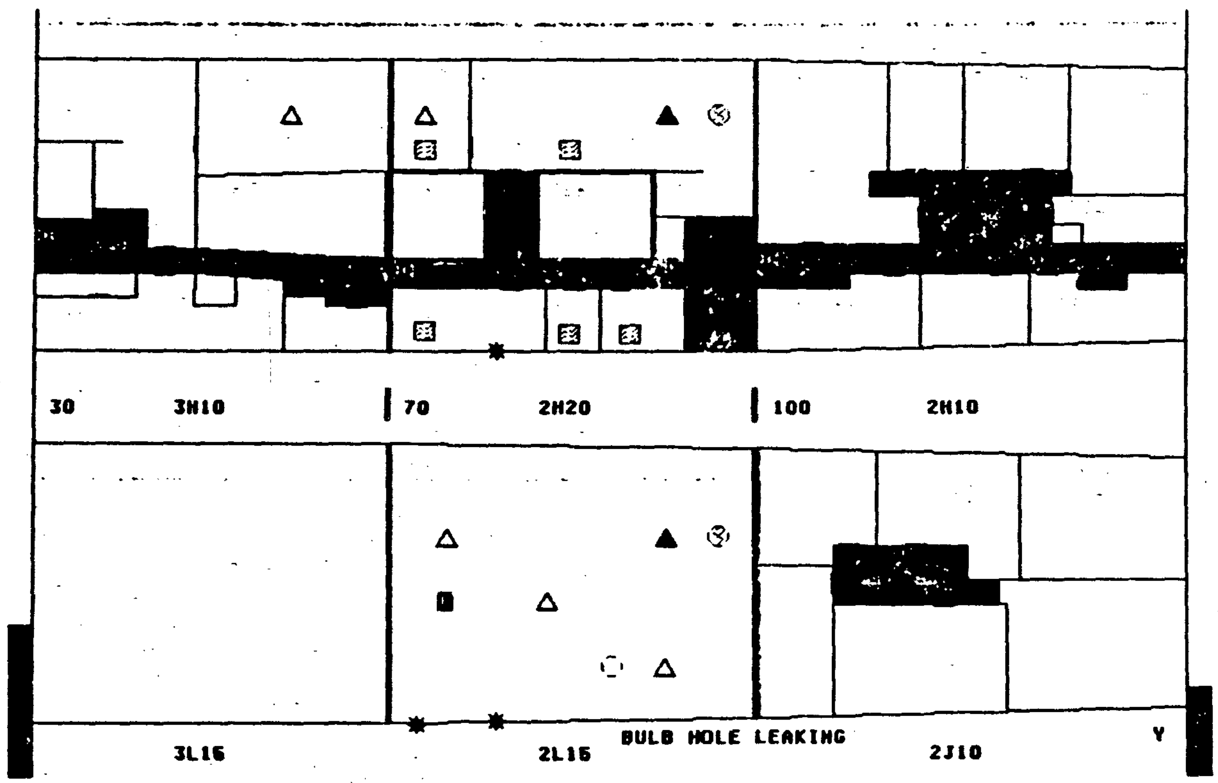

Figure 6. Level 3 DC-plot: vertical view of H- and J-deck above the Forward Engine Room.

9. CONCLUSION

We strongly believe the a feature like the DC-plot presentation system as described here, integrated into a ship's Monitoring and Control System, will improve the overall effectiviness of Damage Control management.
Indeed, as the early experiments have shown, the DC-plots are easy to work with, provide a clear and relatively unambiguous picture to all personnel needing the information, thereby eliminating the bottle-neck in existing procedures.

ADAPTIVE STEERING CONTROL OF INLAND SHIPS

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1. ABSTRACT

On the rivers and canals in Europe there are many inland ships. Many of them are equipped with a simple autopilot to control the rate of turn. It is difficult to tune such an autopilot properly because there is a wide range of difference in the steering characteristics of inland ships and characteristics vary due to varying sailing conditions. To solve this problem an adaptive autopilot for inland ships has been developed. In an indirect adaptation scheme, the parameters of the ship are estimated by a simple but robust projection algorithm. A pole-placement algorithm uses the estimates to tune the controller. The capability of the autopilot has been increased by the addition of course-keeping capabilities. Special attention has been paid to the obtaining of a smooth transfer between rate-of-turn control and heading control. The prototype of the autopilot has been implemented in a VME-bus computer with a 68000 microprocessor. The results of a full-scale trial are reported.

2. INTRODUCTION

Many papers on the steering control of seagoing ships have been written. On the steering control of inland ships, however, little literature is available and the reason may be that in most countries inland ships do not play an important role in the transportation of goods. In European countries, however, they do. Like the helmsmen of seagoing ships, skippers of inland ships appreciate the ease of an autopilot. However, the requirements placed on the autopilot for inland ships are different:

- Control aim: The manoeuvring space of inland ships is much more restricted. Therefore the manoeuvring capabilities (rate-of-turn control) of an autopilot for inland ships are more important than course-keeping capabilities.
- Disturbance rejection: The rate of turn of an inland ship is often influenced by strong and sudden disturbances such as wind gusts and interaction with other ships. The most important disturbances to seagoing ships are waves and a more

or less constant wind momentum.

- Crew: An inland ship is usually sailed by one person only. This is a heavy mental load on the skipper.
- Costs: The cost aspect of an autopilot for inland ships is more important than for seagoing ships. Inland ships are usually owned and sailed by single-owner companies. By working hard the skipper and his family usually earn a marginal income. Obviously, they cannot afford expensive instruments.

The algorithms of the autopilots currently installed on inland ships are simple, but many knobs are necessary for their tuning. They can only control the rate of turn. Most of them are still of an analog type. The disadvantages of the present autopilots are the following:

- The rudder cannot be accurately positioned. There is usually a large dead zone in the rudder controller which leads to a limit cycle and therefore poor steering accuracy.
- Installing and tuning such an autopilot is often difficult and time consuming. An experienced engineer may need more than a day for installation and initial tuning. For the skipper, it is almost impossible to adjust the autopilot to varying sailing conditions such as changes in the load and speed of the ship and the depth and width of the waterway.
- When the skipper wishes to sail a straight course, he sets the desired rate of turn to zero. A small bias in the measurement of the rate of turn, and disturbances may cause the ship to drift from the desired course.

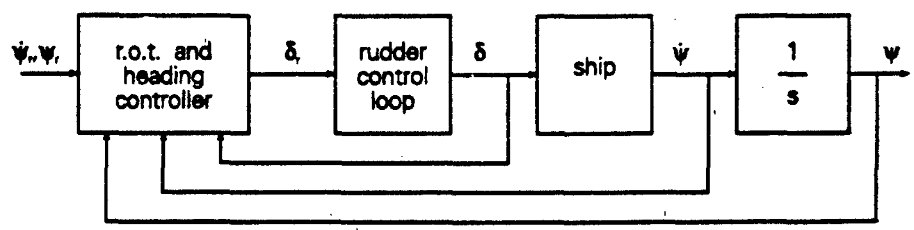
At the Control Laboratory of the Faculty of Electrical Engineering of the Delft University of Technology a research project has been carried out to develop an autopilot without the above-mentioned disadvantages. The autopilot is capable of controlling the ship in three modes:

- rudder control
- rate-of-turn control
- heading control

Figure 1 shows the general structure of the autopilot. The rudder control loop is depicted as an independent subsystem. It has been designed separately from the rate-of-turn and heading controller and it has a higher sampling rate. The local feedback loop eliminates to some extent the nonlinear behavior of the steering machine. Moreover, it allows manual rudder control. This approach is similar to the usual approach to autopilots for seagoing ships.

3. RUDDER CONTROL

The lowest level of control is rudder control. The set point is generated either



δ=rudder angle [deg]; $\dot{\psi}$=rate of turn [deg/s]; ψ=heading [deg]

Figure 1. General Autopilot Structure

manually (rudder-control mode) or by the higher-level controller (rate-of-turn and heading control modes). The rudder of an inland ship is usually positioned by a hydraulic steering machine with electrically actuated valves. The rudder controller must actuate these valves to position the rudder accurately (within 1 deg.) while minimising wear on the steering gear. The wear is mainly related to the frequency with which the hydraulic valves are opened and closed and to the acceleration of the rudder angle.

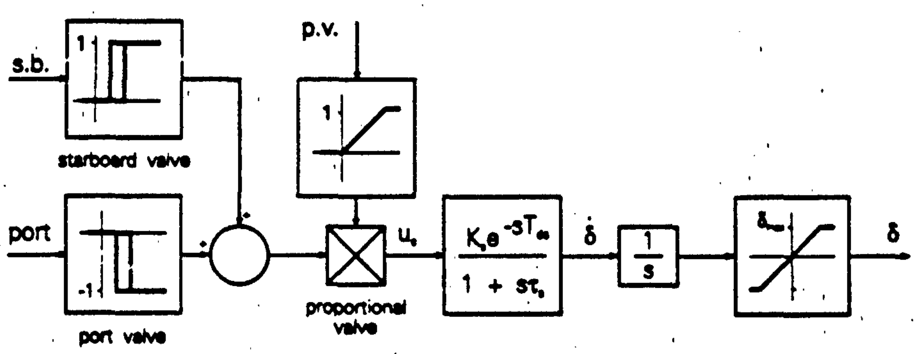


Figure 2. Steering Machine

A general model of a hydraulic steering machine is given in fig. 2. Two valves determine the direction of the rotation. The "proportional valve" controls the hydraulic pressure and therewith the rudder speed. In some steering machines there is no proportional valve. The three valves may also be combined in one. Typical steering machine parameters

are:

$$2.5 \leq K_s \leq 15[°/s] \qquad (1)$$

$$T_{ds}+\tau_s \leq 0.5[s] \qquad (2)$$

3.1 Control with proportional valve

For steering machines with a proportional valve, the rudder controller consists basically of a PD-controller. The derivative action acts on the output only. The output of the controller corresponds with the signal u_c in fig. 2. The actual input signals to the steering machine can easily be derived. To reduce wear, the following measures have been taken:

- A dead zone with hysteresis reduces the frequency with which the valves are opened and closed.
- The rate of the proportional valve opening is limited in order to reduce the forces on the steering gear.
- A time delay ensures that the proportional valve can not open before the port or starboard valve is fully opened.
- The port or starboard valve are not allowed to close before the proportional valve is fully closed.

If tuned well, the controller performance is satisfactory. An automatic tuning procedure determines the maximum rudder speed K_s and the sum of the time delay and the time constant $T_{ds}+\tau_s$. These parameters are used to tune the PD-controller in such a way that no overshoot occurs. An additional problem is that the characteristics of the proportional valve are not ideal. Therefore, the automatic tuning procedure determines the offset and an approximation of the gain of the proportional valve. When the output of the modified PD-controller is translated into the actual input signals of the steering machine, these characteristics are compensated. A typical response of the rudder control loop is given in fig. 3(a).

3.2 Control without proportional valve

In order to achieve fast and accurate responses with minimal wear and without the use of a proportional valve, the steering machine has to be controlled with as few steering pulses as possible. This has been realised by implementing a simple adaptive algorithm (Van Amerongen et all., 1986).

If the dynamics of a relay-actuated process are known, it is possible to generate a table which contains a switching schedule of the relays, in order to turn an angle $\Delta\delta$. When the table is filled with the correct data, the turn is performed correctly as far as the limited discretization of the table allows. When the turn is completed and the final position is not

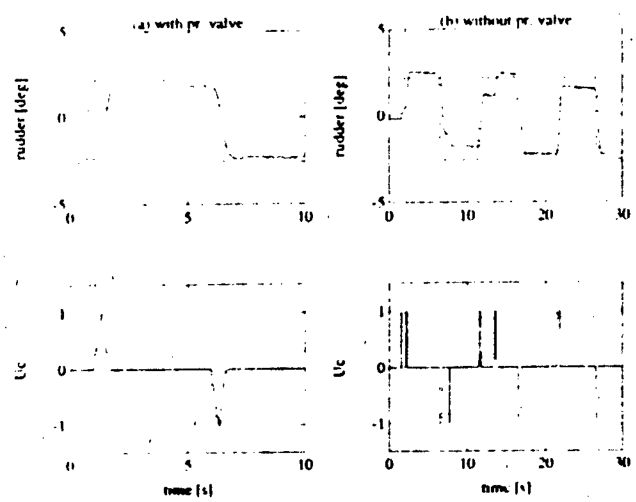


Figure 3. Rudder Control

correct, the actual turn provides information which can be used in an adaptation process:

1. The turn corresponding with the pulse length used is now, in principle, known exactly.
2. Information on how to correct the pulse length of the intended turn is obtained.

In this way the adaptation mechanism adjusts the table to improve the accuracy of the next turn of the rudder.

Table 1. Sample switching table

i	1	2	3	4	5	6	.	12
$\Delta\delta_i$	0.75	1.5	2.25	3.0	3.75	4.5	.	8.0
T_i	0.18	0.27	0.36	0.44	0.51	0.57	.	0.90

The above idea has been worked out and implemented in order to control the steering machine without a proportional valve. The lookup table only contains pulse lengths $\Delta\delta_i$ for rudder turns below a certain limit (e.g. table 1). While the distance between the set point and the starting point of the rudder turn is within the range of the table, the necessary pulse length is calculated using the following formula:

$$T = T_k + \frac{\Delta\delta - \Delta\delta_k}{\Delta\delta_{k+1} - \Delta\delta_k}(T_{k+1} - T_k) \tag{3}$$

where $\Delta\delta$ is the absolute value of the intended rudder turn and

$$\Delta\delta_k \leq \Delta\delta < \Delta\delta_{k+1} \tag{4}$$

At each sampling instant the remaining pulse length is calculated. This signal is applied to a timer which makes it possible to determine the pulse length more accurately than as a multiple of the sampling interval. If, after the turn has been completed, it appears that this interval is not correct the elements of the table nearest to the intended turn are adjusted, assuming linear behavior. The elements nearest to the actual turn are adjusted as well. After the adaptation of these table elements, the table is checked and corrected to be monotonously increasing and to limit the elements based on the a-priori knowledge given by (1) and (2). Separate table are used for port and starboard turns. Figure 3(b) shows the response for a blockwave input. The tables were initially filled with incorrect data.

For large rudder turns, the remaining pulse length is calculated at each sampling instant, assuming that the maximum rudder speed has been attained, and using estimates of the rudder speed K_s and the sum of the time delay and the time constant $T_{ds}+\tau_s$:

$$T = \frac{|\varepsilon_\delta|}{K_s} - (T_{ds} + \tau_s) \tag{5}$$

where ε_δ is the actual rudder angle still to be turned. K_s is estimated from the highest elements of the table and the estimation of $T_{ds}+\tau_s$ is adjusted after the completion of a large turn.

4. ROBUST ADAPTIVE RATE-OF-TURN AND HEADING CONTROL

In this section the design of the rate-of-turn and heading controller as indicated in fig. 1 is described. First, the rate-of-turn model is considered. In section 2, it was stated that the initial tuning and the adjustment to varying sailing conditions of the present autopilots are too difficult. Therefore, whether an adaptive controller can be used is investigated. The properties of the parameter estimator play an important role. Finally, the actual controllers are designed. Special attention is paid to the transfer between rate-of-turn control and heading control.

4.1 Modeling

a. Ship dynamics. Several mathematical models of ships have been proposed for the

purpose of the simulation and design of autopilot systems. The most well-known model is the Nomoto model (Nomoto et all., 1957) represented by:

$$\frac{\psi(s)}{\delta(s)}=\frac{K(s\tau_3+1)}{(s\tau_1+1)(s\tau_2+1)} \tag{6}$$

The structure of this model has been derived from hydrodynamical equations. Measurements taken in several steering trials have been used to determine the parameters for different ships. Nomoto stated that the steering motions of ships are substantially first-order phenomena. The parameters τ_2 and τ_3 were of the same order and much smaller than τ_1 for all ships. Therefore, (6) can be simplified to (7) which is known as the first-order Nomoto model.

$$\frac{\psi(s)}{\delta(s)}=\frac{K}{s\tau+1} \tag{7}$$

For inland ships the ranges of the parameters are given by:

$$0.1\leq K\leq 0.5 \tag{8}$$

$$5.0\leq \tau \leq 50[s] \tag{9}$$

The Nomoto models do not take into account the forward speed drop caused by steering. Hence they are only accurate for small rudder angles. Still, the first-order Nomoto model describes the most important dynamics so it is here used for controller design. The algorithms have to be robust in order to be able to handle possible second-order dynamics and non-linear behavior in large rudder angles.

The Nomoto model describes the dynamics between the actual rudder angle and the rate of turn. The rate-of-turn and heading controller, however, calculates the desired rudder angle. The dynamics of the rudder-control loop therefore have to be considered as well. Fortunately, the rudder-control loop can be tuned in such a way that its dynamics are much faster than the dynamics of the rate-of-turn model. Therefore, these dynamics are not taken into account explicitly in the controller design.

b. Disturbances. An inland ships suffers from various disturbances. Some disturbances are:

- asymmetrical load distribution
- influence of the banks of the waterway
- wind
- ships and other obstacles in the waterway
- waves

Like the rudder of a ship, these disturbances cause a turning moment. Therefore, these disturbances are considered to act on the input of the ship's model. The first three

disturbances normally have large low-frequency components. They can be regarded as a slowly varying offset. For the higher-frequency components of the wind, for example gusts, and the latter two types of disturbances, it is hard to formulate a general model. They do not have a more or less regular nature like waves at sea. For some of these disturbances, however, time-domain models are available. These models can be used to test the autopilot during simulations.

There are also disturbances which act on the ship's parameters:
- changes in load
- depth of the waterway
- speed of the ship

These disturbances are assumed to have mainly low-frequency components. This category of disturbances can be better described as changing sailing conditions.

4.2 Adaptive control

In section 4.1(a) it has been indicated that the parameters of the rate-of-turn model vary over a wide range for different ships and also vary due to varying sailing conditions. Adaptive control can be used to track the process parameters and to tune the controller accordingly. However, a successful implementation of adaptive control requires that:
- Control must be stable, even when the estimation of the parameters has not yet converged.
- The process has to be sufficiently excited.
- Unmodeled process dynamics, which are always present, and disturbances may not lead to instability of the parameter estimator or the controller.

The first condition sets requirements with regard to the quality of the initial estimates and to the robustness of the controller. For most processes, the condition of sufficient excitation is not fulfilled. The steering dynamics of a seagoing ship are excited when it leaves the harbor, but thereafter there may not be a considerable excitation for a couple of days. Inland ships, however, have to manoeuvre constantly in order to follow the path of the waterway and to avoid collisions with other ships. Consequently, the dynamics of inland ships are sufficiently excited to allow adaptive control. It has been indicated that unmodeled dynamics may be present in the form of second-order dynamics non-linear behavior in large rudder angles and disturbances. Therefore, attention has to be paid to the robustness of the parameter estimator and the controller with respect to unmodelled dynamics.

Since the possible range of the parameters is known, the parameter estimation can be monitored and action can be taken if it diverges, to do so, it is necessary to choose an indirect adaptation scheme. Another advantage of this scheme is that it allows the freedom to design the parameter estimator and the controller separately. For these reasons, the indirect

adaptation scheme has been selected. A robust parameter estimator explicitly estimates the parameters of the first-order Nomoto model. These estimates are used by a tuning algorithm to calculate the parameters of the rate-of-turn and heading controller.

4.3 Parameter estimation

A simple but robust parameter estimator is the projection algorithm (Åström and Wittenmark, 1989):

$$\hat{\theta}(t)=\hat{\theta}(t-1)+\frac{\gamma\varphi(t)}{\alpha+\varphi^{T}(t)\varphi(t)}(y(t)-\hat{\theta}^{T}(t-1)\varphi(t)) \tag{10}$$

with:

$$\alpha\geq 0, 0<\gamma<2 \tag{11}$$

In (10) the model is represented by:

$$y(t+1)=\theta^{T}\varphi(t) \tag{12}$$

with Θ as the parameter vector and $\varphi(t)$ as the signal vector. The Z-transform of the first-order Nomoto model (7), assuming zero-order hold, offers:

$$\frac{\psi(z^{-1})}{\delta(z^{-1})}=\frac{b_1 z^{-1}}{1-a_1 z^{-1}} \tag{13}$$

In section 4.1 it was indicated that there may be an offset. This yields, together with (12) and (13):

$$\psi(t+1)=a_1\psi(t)+b_1\delta(t)+c \tag{14}$$

with c as the offset. From (14) Θ and $\varphi(t)$ can be constructed. The effects of unmodeled dynamics and disturbances have to be kept small while the speed of convergence must remain acceptable. Therefore, it is important that the adaption speed of the individual parameters can be tuned carefully. By scaling the elements of the signal vector $\varphi(t)$ the adaptation speed of the corresponding parameters in Θ can be influenced.

The product $\varphi(t)^{T}\varphi(t)$ in the denominator of (10) normalizes the adaptation speed, i.e. it makes the adaptation speed independent of the length of the signal vector $\varphi(t)$ if $\alpha=0$. Normalization is important when unmodeled dynamics are present since the amplitude of the error signal caused by unmodeled linear dynamics is proportional to the amplitude of the input signal. The amplitudes of the individual signals which constitute $\varphi(t)$ have to be of the same order in order to allow all signals to contribute equally to the normalization factor. Appropriate choices for Θ and φ are:

$$\theta = (a_1\bar{K},\ b_1,\ \frac{c}{\bar{c}})^T \tag{15}$$

$$\varphi(t) = (\frac{\dot{\psi}(t)}{\bar{K}},\ \delta(t),\ \bar{c})^T \tag{16}$$

The reach of the rudder angle δ is of the same order for all ships. This signal is not scaled. The reach of the output signal ψ is related to that of δ by the DC-gain K of (7). Therefore the output signal ψ is scaled to φ_1 by a factor of $\bar{K}^{-1}$, where $\bar{K}$ is the a-priori estimation of K. Estimation of the offset c has to dominate over the estimation of the other parameters when the input and the output signals are small. The signal φ_3 is a constant which corresponds with a small rudder angle, say 5 deg. Since φ_3 is a constant, $\varphi(t)^T\varphi(t)>0$ so the estimator parameter α can be chosen zero. With the estimator parameter γ the global adaptation speed is tuned.

4.4 Rate-of-turn and heading control

In fig. 1 the rate-of-turn controller and the heading controller are combined into one controller. The autopilot discussed in this paper is, like other autopilots for inland ships, operated via a single steering handle. The handle has a clear middle position. If it is in the middle position the autopilot controls the heading. If not, the rate of turn is controlled (Duetz and Van den Bosch, 1989). By combining the rate-of-turn controller with the heading controller unnecessary transients can be avoided. This can be achieved by introducing a reference model and a feedforward path (Aström, 1984) into the rate-of-turn controller. If the model has been estimated correctly, integral action only has to deal with constant disturbances. Then, the same integral action can be used in the heading control mode too.

a. Rate-of-turn control. In fig. 4 the rate-of-turn control loop has been depicted with H_1 as the ship dynamics (13), H_r the reference model, $\hat{H}_1$ the estimated ship dynamics and H_c the controller. H_1 also contains the relatively fast rudder control loop. An ordinary PI-controller performs satisfactorily. Although the inverse function of $\hat{H}_1$ cannot be realized, when an appropriate choice of H_r is made, the product of H_r and $\hat{H}_1^{-1}$ can be realized. The transfer function of fig. 4 is given by:

$$\frac{\psi}{\psi_r} = \frac{(H_1\hat{H}_1^{-1}+H_1H_c)H_r}{1+H_1H_c} \tag{17}$$

Clearly, if the transfer function H_1 is estimated accurately, the ship will behave according to the reference model.

The structure of fig. 4 makes it possible to define the disturbance-rejection dynamics

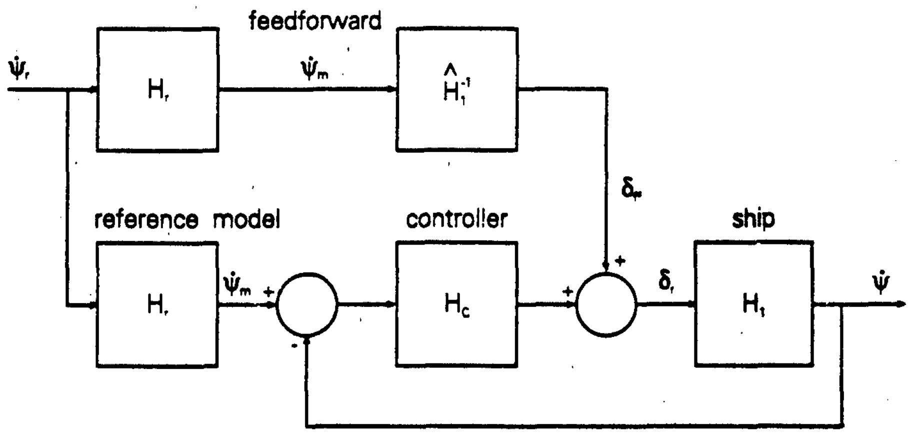


Figure 4. Rate-of-Turn Control Loop

separately from the tracking dynamics. Pole-placement has been used to determine the parameters of the PI controller and the reference model. The desired locations of the poles depend on the estimated dynamics. This relation has been determined experimentally (Duetz and Van den Bosch, 1989). The closed-loop poles do not have the same locations as the poles of the reference model. The settings of the PI rate-of-turn controller are denoted by K_{pr} and K_{ir}, respectively.

b. Heading control. When the skipper sets the desired rate of turn to zero the autopilot switches from rate-of-turn control to heading control. The course ψ on which the ship is sailing at that particular moment becomes the set point ψ_r of the heading controller. No important set-point changes can be made during heading control. Therefore, only a feedback controller is used. Feedback of the heading and the rate of turn results in a PD controller. An additional integral action is necessary to compensate for constant disturbances. In a way similar to that used in the rate-of-turn controller pole-placement is used to determine the controller gains. The PID controller gains are denoted by K_{ph}, K_{ih} and K_{dh}.

c. Transient. The switching between rate-of-turn control and heading control has to be smooth and without undesirable transients. To achieve this aim, the controller structure shown in fig. 5 is introduced. In the rate-of-turn mode the following settings are selected:

$$K_{\psi}=0;\ K_{\psi}=K_{pr};\ K_i=K_{ir} \tag{18}$$

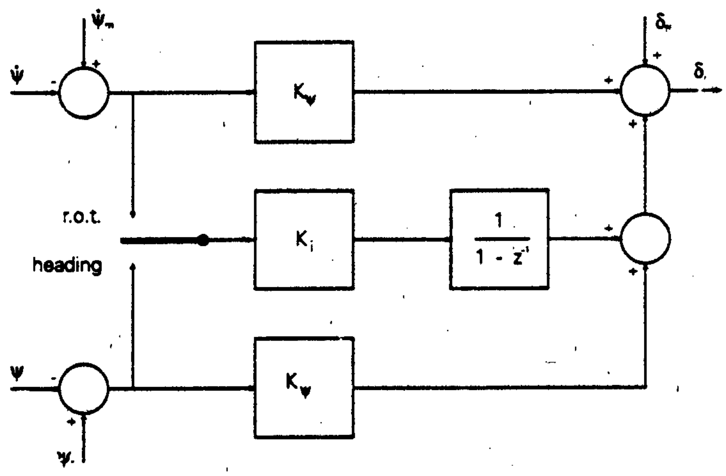


Figure 5. Mixed-Mode Contuoller Structure

In the heading mode these setings are given by:

$$K_\psi = K_{ph};\ K_{\dot\psi} = K_{dh};\ K_i = K_{ih} \tag{19}$$

When the controller mode has been changed from rate-of-turn control to heading control, the integration of the error is stopped during the transient. During that time the controller settings are changed smoothly to their new values. This avoids large and sudden changes of the desired rudder angle which causes the rudder-control loop to saturate and, consequently, might give stability problems. Both controllers use the same integrator for the integral action. Thus, a mode switch will not introduce transients as a consequence of erroneous values of the initial value of the integrator. When the model has been estimated correctly, the output of the integrator represents a constant offset on the rudder.

5. RESULTS

The algorithms described in this paper have been programmed in C language. The program runs under the operating system OS9 on a VME-bus computer with a 68000 microprocessor. A number of full-scale trials has been held during the project using this setup. The same operating system and microprocessor are used in the commercial product.

Some results of a full-scale trial with the "Duo", an inland tanker of 33m in length

are presented. Figure 6 shows the identification results obtained during the sailing trial which is necessary to determine the startup settings of the autopilot. The estimated parameters of the discrete-time model (13) are translated into the parameters of the first-order Nomoto model (7). The parameter estimator appears to perform satisfactorily. The estimates converge with an acceptable speed.

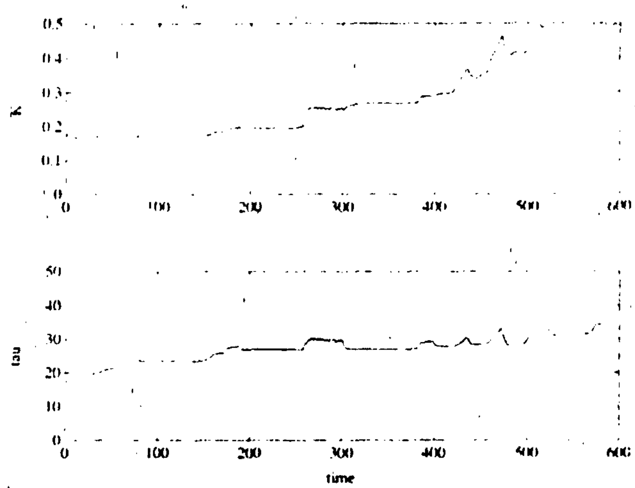


Figure 6. Results Parameter Estimation

Figure 7 shows the performance of the rate-of-turn controller after the convergence of the parameter estimator. The responses to set point changes are accurate and stable. The actual rate of turn is quite similar to the output of the reference model and the rudder angle resembles the feedforward rudder angle. This indicates that an acceptable estimation of the ship dynamics has been achieved.

Heading control is shown in fig. 8. At $t=t_1$, the skipper started heading control by setting the steering handle in the middle position while the ship was turning at a rate of about -4 deg/s. Due to the limited bandwidth of the control loop an overshoot occurs but the controller brings the ship back to the desired heading.

6. CONCLUSIONS

There are important differences between steering seagoing ships and steering inland

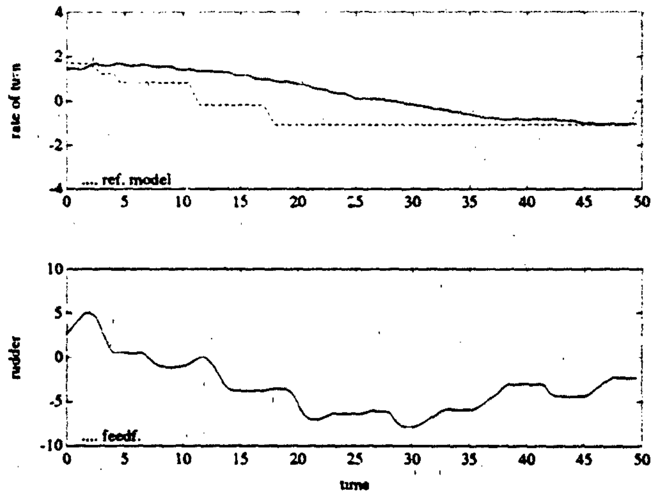


Figure 7. Results Rate-of-Turn Control

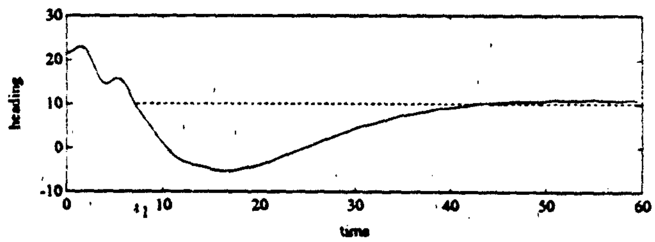


Figure 8. Results Heading Control

ships. In this paper the development of an autopilot for inland ships has been described.

Several disadvantages of autopilots currently available have been alleviated. Accurate rudder positioning algorithms have been developed for different types of steering machines. Adaptive control has been introduced to facilitate initial tuning and to adjust the autopilot to varying sailing conditions. An indirect adaptation scheme with a simple, robust parameter estimator performs adequately. Besides the rate of turn, the autopilot is capable of controlling the heading. The autopilot can still be operated with one steering handle. The selected controller structure guarantees a smooth transfer from one controller mode to the other.

A full-scale trial was successful. A commercial realization of the proposed autopilot will reach the market in 1990.

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WARSHIP ROLL STABILISATION USING INTEGRATED CONTROL OF RUDDER AND FINS

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1. ABSTRACT

Traditionally roll stabilisation of warships is achieved using a hydraulically controlled fin stabiliser system. In recent years roll stabilisation by means of the rudder alone has been proposed, although this approach can prove to be a more expensive solution because of the increased rudder speeds necessary. In this paper we describe a roll stabilisation system which uses integrated control of the rudder and the stabilising fins. Following the development of mathematical models of typical warship dynamics and wave disturbances, controller designs using classical frequency domain techniques are presented. The results from computer simulation studies are used to demonstrate the enhanced roll stabilisation which can be achieved using existing control surfaces.

2. INTRODUCTION

Since 1956 every combatant ship built for the Royal Navy has been fitted with an active roll stabilisation system. The justification for this was to meet the operational requirement of maintaining a stable platform. The case for warship roll stabilisation was further reinforced with the advent of the shipborne helicopter in the 1950's. Despite the increased operating limits which will be achieved by the new generation of helicopters such as the EH101 there remains the requirement to minimise roll motion during essential operations such as recovery, rearming and refuelling.

Roll stabilisation in the majority of warships is achieved by active control of sets of hydraulically operated stabilising fins, and to date their performance is unrivalled. In recent years however there has been considerable interest in the technique of roll stabilisation by means of the rudder. With this approach fin stabilisers are not fitted, and roll motion introduced by rudder displacement is used to counteract the roll motion resulting from

sea state disturbances. The concept of rudder roll stabilisation is not new, it was first described by Cowley and Lambert (1) in 1972, with later contributions by Lloyd (2), Carley (3), Amerongen and others (4), (5), (6) and Katebi et al (7). The first successful sea trials were reported in 1980 by Baitis (8) who used manual steering. In later trials, described by Baitis and Woolaver (9), Amerongen et al (10), Roberts (11) and Klugt (12), rudder roll stabilisation is included as an integral part of the steering autopilot.

The research work cited above has established that, for warships of frigate size, rudder speeds of the order of $20^{o}.s^{-1}$ are necessary for the rudder to be as effective at roll reduction as stabilising fins. This is a significant increase in speed compared with rudder systems currently fitted to frigates, which have speeds of typically $6^{o}.s^{-1}$. The provision of a rudder system which has the desired speed results in significant cost increases by way of increasd hydraulic power requirements and the need for larger stock bearings etc. This means that the adoption of this technique can only be considered a viable option for ships at either the design stage or 'retro-fitting' during a major refit programme.

Although the effectiveness of a rudder roll stabilisation system is governed by rudder speed it is however possible to obtain a measure of roll reduction using the existing 'slow' rudder system. This forms the basis of the work described herein where it is proposed that roll stabilisation is achieved using the rudder to assist, rather than replace, the existing fin stabilisation system. It should be noted that this method differs from the concept of an integrated control of roll and yaw motions, (13), (14), (15). In this case the rudder to roll cross-coupling effect is utilised to achieve roll reduction, rather than using rudder and fins in concert to reduce the interaction between the roll and yaw control loops.

3. SIMULATION MODEL

3.1 Warship Dynamics

The Royal Navy frigate considered in this study was selected as it represents a class of warship where subsantial roll reduction is achieved utilising conventional fin stabilisers. The proposed integrated control strategy using rudder and fins for roll stabilisation is shown by Figure 1. The dynamics representing the roll responses to fin and rudder, and the yaw to rudder angle response, are adapted from the model proposed in (15) and later validated and updated by Roberts (16), (17). The dynamics were obtained from data from sea trials at ship speeds of 12, 18 and 26 knots. Details of the individual component transfer functions are given in Table 1. A combination of hull shape and the position of

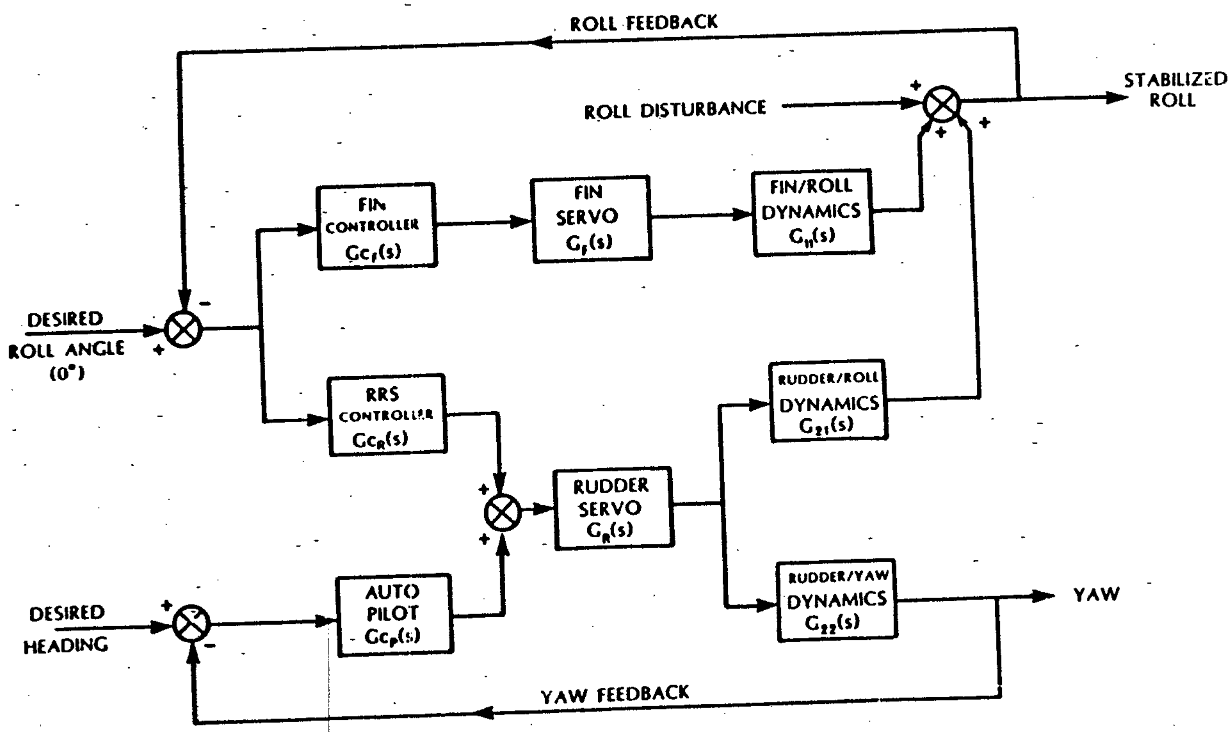

Figure 1 Configuration for Steering and Roll Stabilisation

the two sets of stabilising fins with respect to the yaw axis, results in negligible fin angle to yaw cross-couple. The non-linearity of warship dynamics are represented by variation of steady-state gain terms with speed, as shown in Table 2.

Table 1 - Elements of Warship Dynamics

$$G_{11}(s) = \frac{0.25k_{11}}{s^2+0.235s+0.25}$$

$$G_{12}(s) \quad \frac{0.25k_{12}(1-8.57s)}{(1+8.2s)(s^2+0.25s+0.25)}$$

$$G_{22}(s) = \frac{k_{22}}{s(1+0.43s)(1+6.62s)(1+4.18s)}$$

Table 2 - Gain Variations

speed knots	k_{11}	k_{12}	k_{22}
12	0.114	-0.33	0.01
18	0.18	-0.465	0.02

3.2 Actuator Dynamics

The hydraulic servomechanisms used to power the steering gear and the stabiliser fins will introduce additional non-linearities which must be taken into account. The rate at which either actuator can move is a function of the physical size of the mechanical system, and the range of actuator movement is restricted by practical considerations. In this study these systems were modelled using the approach proposed by Amerongen (18).

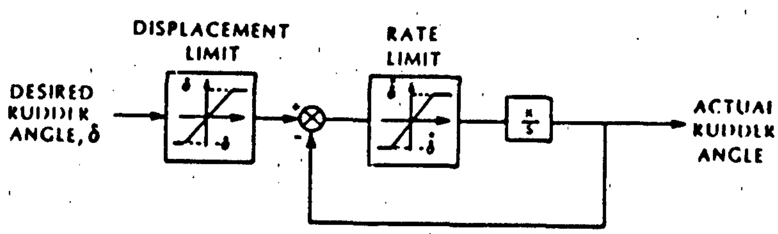

Figure 2 Steering Gear Model

A block diagram representing a model of the operation of the steering gear is shown in Figure 2. A similar approach was used to model the stabiliser fin servomechanism. For the class of warship considered, the rate limit for the rudder is $6^{o}.s^{-1}$ and maximum travel is restricted to $\pm 35^{o}$. Rudder movement is rate limited whenever the error between achieved and demanded rudder angle is greater than 3^{o}. Rudder movement is linear for errors of less than 3^{o}. The values of rate limit and displacement limit for the fin servomechanism are $+30^{o}.s^{-1}$ and $\pm 29^{o}$ respectively.

3.3 Roll Controller and Autopilot

The transfer functions representing the roll controller and autopilot are given by:

$$\text{Roll controller, } Gc_F(s) = \frac{k_g k_u (k_1 + k_2 s + k_3 s^2)}{b_1 + b_2 s + b_3 s^2} \qquad (1)$$

$$\text{Autopilot, } Gc_P(s) = \frac{k_4 (1 + sT_1)}{(1 + sT_2)} + \frac{k_5}{T_3 s} \qquad (2)$$

The coefficients used for the roll controller and autopilot reflect those currently in service with the Royal Navy. Therefore simulation results obtained for the warship model with the standard fin stabilisation system can be compared directly with data reflecting actual ship performance to provide the benchmark against which the performance of the integrated roll stabilisation control strategy can be assessed. The integration term $k_5/T_3 s$ represents the 'weather helm' and was not incorporated for the simulation study.

4. SEA STATE DISTURBANCES

The accurate representation of the sea state is one of the fundamental issues in studies of ship behaviour. The application of statistical methods, based on visual observations of the sea surface and theoretical wave spectrum formula, provide a suitable approach for describing the characteristics of irregular waves. An irregular wave time history can be expressed as a sum of an infinite number of sinusoidal waveforms. The relative importance of the component sine waves can be taken into account by describing the waves in terms of a wave energy spectrum. The Bretschneider or ITTC two-parameter wave energy spectrum formula provides an appropriate representation of open ocean wave conditions and is defined by the relationship:

$$S(\omega) = \frac{A \exp(-B/\omega^4)}{\omega^5} \qquad (3)$$

where:

$$A = \frac{72.75H^2}{T^4} \qquad (m^2.s^{-4}) \qquad (4)$$

$$B = \frac{691}{T^4} \qquad (s^{-4}) \qquad (5)$$

An irregular wave history having a frequency spectrum which approximates to that of a Bretschneider spectrum can be generated by a system comprising a white noise generator and a second-order low-pass filter (13). A block diagram representation of this is shown by Figure 3. This method of simulating sea state disturbances was used in this study.

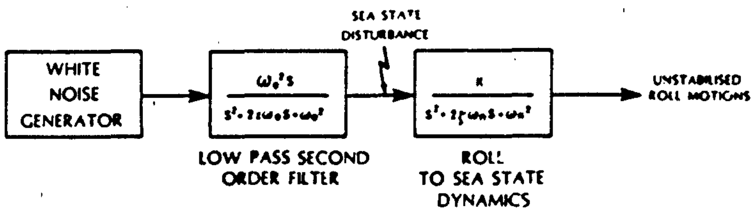

Figure 3 Wave Simulation Model

Ship motions in a seaway are complex and are dependant on a number of factors, the most significant of these are the frequency at which the moving ship encounters the waves, and the roll moment exerted on the ship by the waves. The effect of ship's speed and the relative heading with respect to the wave direction can be taken into account by adjustment of the encounter frequency ω_e, of the low-pass filter in the wave model, in accordance with the relationship:

$$\omega_e = \omega_o + (u\omega_o^2 \cos\gamma)/g \qquad (6)$$

where: ω_o = Characteristic wave frequency (rad.s^{-1})

u = ship's speed (m.s^{-1})

γ = angle between ship's head and wave direction

g = acceleration due to gravity (m.s^{-1})

The roll moment exerted by the waves is also dependant on the attitude of the ship to the wave system. In a head sea the roll

moment is a minimum, whilst for a beam sea the roll moment will be a maximum. The application of strip theory techniques to represent the three-dimensional hull form and the effect of wave excitations, provides one approach which accounts for this phenomenum. An alternative approach, which was used in this study, is to equate the roll moment at a given heading to the effective natural damping ratio of the modified roll to fin transfer function used in the wave simulation model. For example, in a head sea where the roll moment is a minimum the damping is set to a maximum and likewise for a beam sea the roll moment is a maximum and the damping is set to a minimum. This relationship between roll damping and ship's head is depicted by Figure 4.

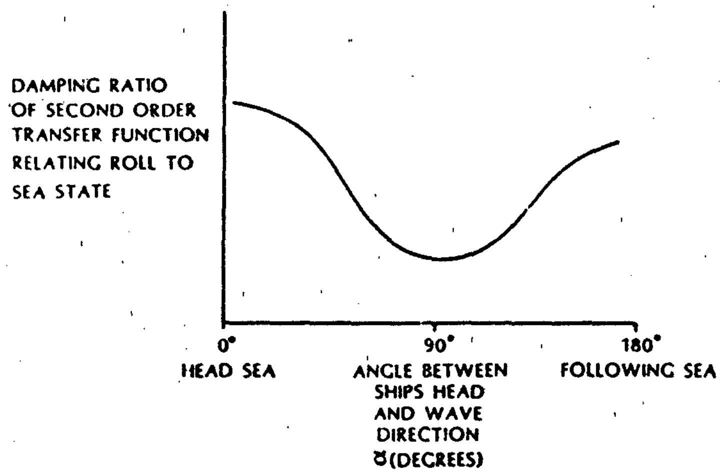

Figure 4 Variation of Roll Damping with Ship's Head

Using the approach described above the simulated unstabilised and stabilised roll motions generated over the range of encounter angles compared favourably with roll motions experienced by the actual warship at sea. This therefore confirmed the validity of the 'benchmark' and engendered confidence in the suitability of the models and the modelling process to replicate actual ship performance at sea.

5. CONTROLLER DESIGN

The aim of the roll stabilisation system is to ensure that the roll moment generated by the control system opposes the roll moment generated by the waves. In order for the rudder to be used to counter sea induced roll motions, without adversely affecting yaw, the dynamic relationships between rudder and roll must be faster than those between rudder and yaw. Frequency response plots of the

rudder to yaw dynamics $G_{22}(s)$, and the rudder to roll dynamics $G_{12}(s)$, are shown in Figure 5, where frequency separation between yaw and roll motion is evident. This frequency separation between the roll and yaw control loops allows a decoupled yaw and roll approach to be taken with respect to rudder-roll controller design. Before describing the controller design however, it is useful to first consider the existing fin stabilisation system.

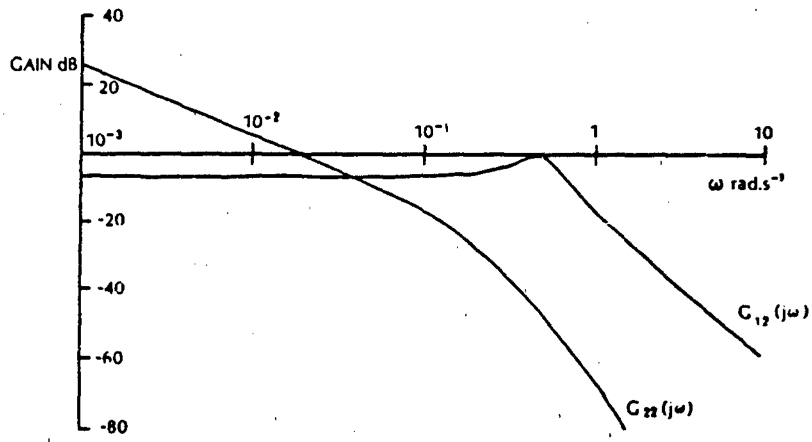

Figure 5 Roll Frequency Responses

5.1 Fin Stabilisation Controller Design

The existing roll stabilisation configuration is shown by Figure 6.

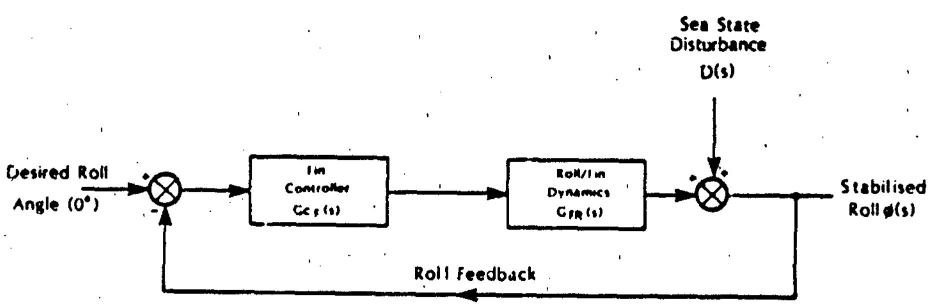

Figure 6 Existing Roll Stabilisation Control Loop

It can be seen from this figure that the desired roll angle or set point is zero degrees, and the transfer function relating roll motion to sea state disturbance is defined by:

$$\frac{\phi(s)}{D(s)} = \frac{1}{1 + Gc_F(s)G_{FR}(s)} \qquad (7)$$

where $G_{FR}(s)$ represents the combined effect of the roll fin transfer function $G_{11}(s)$, and the transfer function of the fin servomechanism $G_F(s)$.

Using classical frequency-domain sensitivity analysis it is seen that roll reduction will occur providing that the modulus of $[1 + Gc_F(j\omega)G_{FR}(j\omega)]$ is greater than unity over the frequency range of interest. The performance of the roll stabilisation system can therefore be assessed by consideration of the Nyquist locus of $Gc_F(j\omega)G_{FR}(j\omega)$. Figure 7 gives a typical roll control loop Nyquist locus where it can be seen that at a particular frequency $|1 + Gc_F(j\omega)G_{FR}(j\omega)|$ represents the distance from the (-1,0) point to the $Gc_F(j\omega)G_{FR}(j\omega)$ locus, and hence roll reduction occurs for all those frequencies for which the Nyquist locus lies outside the unit circle centred at (-1,0). Conversely, amplification of roll motion will occur at frequencies for which the Nyquist locus lies inside the unit circle.

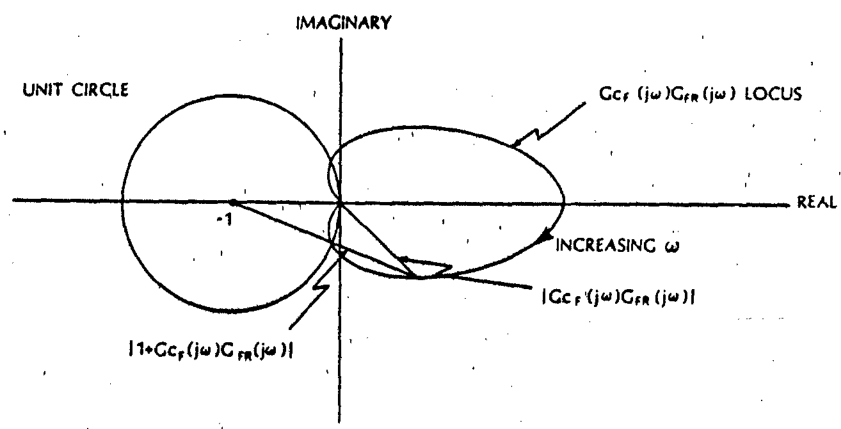

Figure 7 Typical Roll Loop Nyquist Locus

Lloyd (19) has shown that satisfactory roll reduction over the frequency range of interest can be achieved if the phase angle of $Gc_F(j\omega)G_{FR}(j\omega)$ is zero at the ships natural frequency $_n$. Consequently, roll controller design involves selecting the controller coefficients (equation 1) in order to introduce a phase-advance equal to the phase-lag resulting from the warship's roll dynamics and the fin servomechanism, whilst at the same time ensuring that the frequency at which the $Gc_F(j\omega)G_{FR}(j\omega)$ locus enters the unit circle is kept as high as possible.

5.2 Rudder Roll Stabilisation Controller Design

The configuration for roll stabilisation by the rudder alone is shown by Figure 8, where $G_{RR}(s)$ represents the combined effect of the rudder/roll transfer function $G_{12}(s)$, and the transfer function of the rudder servomechanism $G_R(s)$.

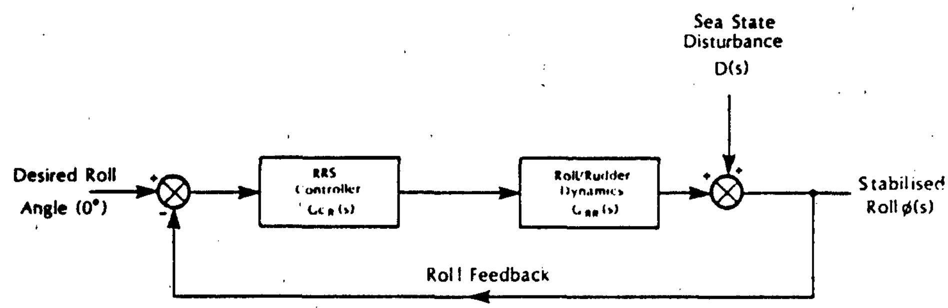

Figure 8 Rudder Roll Control Configuration

The aim here however is to produce a roll stabilisation system using the rudder which assists the stabilisation produced by the fins. The control configuration is therefore that depicted by Figure 9, for which the transfer relating roll to sea state disturbance is defined as:

$$\frac{\phi(s)}{D(s)} = \frac{1}{1 + Gc_F(s)G_{FR}(s) + Gc_R(s)G_{RR}(s)} \qquad (8)$$

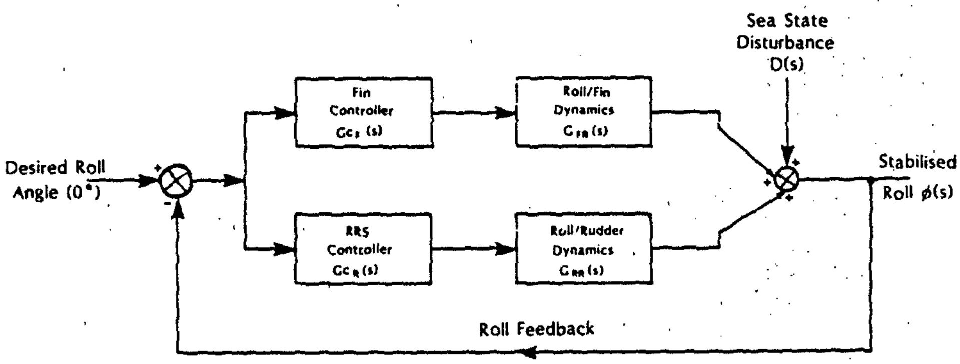

Figure 9 Integrated Fin and Rudder Roll Stabilisation Configuration

In this configuration roll reduction clearly results from the combination of the fin/roll and rudder/roll control loops, and ideally controller design should take account of this. However, in addition to producing enhanced roll stabilisation it is possible that in some circumstances, dictated by operational requirements, roll stabilisation using the rudder alone could be considered as an alternative to fin stabilisation. In this study therefore, the two roll stabilisation loops were considered to be independent for controller design, and using design ideas outlined above the rudder roll controller $Gc_R(s)$, was selected to have the general form:

$$Gc_R(s) = \frac{k_S(k+k_R s+k_A s^2)}{A_1+A_2 s+A_3 s^2} \qquad (9)$$

where:

k_S = Speed dependant gain
k = Roll angle sensitivity
k_R = Roll rate sensitivity
k_A = Roll acceleration sensitivity

In this case the controller has to compensate for the phase lag introduced by the rudder to roll dynamics $G_{12}(s)$, and the rudder servomechanism $G_R(s)$. As with the fin controller design this phase advance is tuned by the selection of k, k_R and k_A. Having obtained the required phase advance the speed related gain term k_S, is adjusted to maintain an adequate gain margin. The denominator coefficients are chosen to provide a degree of high frequency filtering whilst introducing minimal phase lag at the

ship's roll natural frequency.

Controller designs using three-term and two-term control action were considered. Adopting the guidelines given in (7) the roll angle sensitivity k, was selected to be small compared with roll rate sensitivity k_R, and roll aceleration sensitivity k_A. Results obtained for two, three-term and two, two-term controllers are presented here. The four controllers considered are defined below:

(1) (three term controller) $k = 1.0$, $k_R = 5.0$, $k_A = 6.2$

(2) (three term controller) $k = 1.0$, $k_R = 10$, $k_A = 8.2$

(3) (two term controller) $k = 0$, $k_R = 2.4$, $k_A = 1.0$

(4) (two term controller) $k = 1.0$, $k_R = 9.4$, $k_A = 0$

Digital simulation studies enabled the performance of the above integrated fin and rudder control strategy to be investigated for all the controller configurations over a range of ship speeds, sea states and encounter angles. In each case a simulation time of 500 seconds was used and values of stabilised roll angle(rms), maximum roll angle, yaw disturbance and rudder activity were recorded. As an example the results obtained for a ship speed of 18 knots in a sea state 5 are summarised in Table 3.

The encounter angles for bow, beam and quarter seas are for the ranges 10°-20°, 90°-120° and 150°-170° respectively. The roll reduction is defined by:

$$\%\ \text{roll reduction} = 1 - \frac{\text{stabilised roll(rms)}}{\text{unstabilised roll(rms)}} \tag{10}$$

Table 3 - Results Summary (18 knots, Sea State 5)

CONTROL MODE	INCREASED ROLL REDUCTION bow	beam	quarter	RUDDER ACTIVITY($^{\circ}$rms) bow	beam	quarter
(1)	5%	11%	6%	3.6	3.6	0.24
(2)	-1%	13%	2%	3.7	4.3	0.32
(3)	-2.5%	12%	-8%	3.7	4.4	0.43
(4)	-11%	6%	4%	3.8	4.5	0.41

6. DISCUSSION

Simulation results for the four controllers considered indicated a negligible mean heading error for all encounter angles, and that the maximum yaw deviation from the set course does not exceed 0.5°.

A negative sign for increased roll reduction in Table 3 indicates that the combined stabilisation system is not as effective as the fin stabilisation system alone. However, this does not necessarily indicate roll amplification of unstabilised roll has occurred although this was the case, in a bow sea, for controller (4).

The increase in roll reduction provided by all controllers is a maximum, and of the same magnitude, in the vicinity of a beam sea. The enhanced roll reduction achieved by the control system in these seas is particularly significant as it represents the conditions where unstabilised and fin stabilised roll motions are a maximum.

The bandwidth of increased roll reduction provided by the combined stabilisation system is wider for the three-term controllers. The bandwidth of controller (1) is marginally greater than that of controller (2), in addition the rudder activity for controller (1) is lower for the range of headings considered.

7. CONCLUDING REMARKS

In this paper we have presented the results of a design study into the feasibility of improving warship roll stabilisation using an integrated rudder and stabilising fin control strategy.

The main advantage of adopting this approach is that improved roll stabilisation can be achieved using existing sensors and actuators, and it is therefore suitable for retro-fitting. In addition this approach to roll stabilisation allows the command flexibility as it would be possible to select either fin roll stabilisation, rudder roll stabilisation or integrated rudder and fin roll stabilisation. A decision which can be made in the light of the tactical situation.

Further simulation studies are being conducted to establish the overall operating performance of the combined stabilisation system. In particular the stabilisation characteristics of the rudder alone, and the reduced fin activity of the combined system are being examined.

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STABILIZATION SYSTEM AND MANOEUVRING PROCEDURES FOR THE FUTURE FRENCH NUCLEAR AIRCRAFT CARRIER

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1. ABSTRACT

Much research has been carried out for the future French Nuclear Aircraft Carrier. For this, a multicriteria automatic pilot has been developed to ensure operational performance. Two modes of the pilot are described in this paper: stabilization during straight courses and piloting during gyrations. Horizontal movements, such as sway, roll, yaw and motions of several specific points, are controlled to assist landing and catapulting. The command system uses two pairs of lateral independant fins, one pair of steering rudders and a heel compensation system (water tanks).

To stabilize the ship during straight course, a multivariable adaptive control technique has been used (linear quadratic algorithm). Moreover, an optimization procedure calculates for the gyration the ballast transfers and determines a reference trajectory to reach a new course with a maximum heel constraint. All the methods have been implemented aboard a free scale model (1/12th scale) which was entirely instrumented for this occasion. The sea tests have permitted since october 1987 the first validation and the evaluation of the performances.

2. INTRODUCTION

In order to increase the operational capabilities of the future French Nuclear Aircraft Carrier, different means have been employed. First, several possible hull forms were reviewed during a computer assisted phase; in view of the results, it has been decided to decrease the transverse stability module in opposite with the oldest aircraft carriers, such as the "CLEMENCEAU": 1.5 meters, as opposed to 2.5 meters giving a natural stabilization benefit via demodulation. Indeed, increasing in this way the natural period of the roll, we move away from the modal periods of the most likely encountered seas. The main purpose being to comply with some seakeeping criteria (cf table 1) up to a sea state of force 5/6, these structural modifications alone are not sufficient. Therefore, the N.A.C. will be equipped with an active control system (system S.A.T.R.A.P.), allowing ship motion stabilization and heel recovering to respect the constraints of all the AVIA operations.

Summarizing, the stabilization system should be able to satisfy two different sorts of duties:

— comfort improvement in aircraft operations for sea states where these operations could, however, be possible even if active control did not exist

— aircraft operation in sea states in which they would be otherwise impossible

To meet this goal, it will dispose of two pairs of lateral independant fins and one pair of steering rudders. Moreover, a water tank system will be used to reduce the heel due to the wind, the changes of load and the gyrations. Indeed, such a device will permit a simultaneous decrease in every horizontal ship motion around the mean trajectory, not only in straight courses but also in gyrations or changes of course.

AVIA operations	motions involved in criterion	comfort limit	operational limit	absolute limit
aircraft manoeuvres on flight-deck	*roll* *lateral acc.*	*1 degree* *0.2 m/s2*	*3 degrees* *0.6 m/s2*	*5 degrees* *1 m/s2*
catapulting	*roll* *yaw velocity* *lateral acc.*	*1 degree* *0.3 degree/s* *0.5 m/s2*	*3 degrees* *1 degree/s* *1.5 m/s2*	*5 degrees* *1.5 degree/s* *2.5 m/s2*
landing	*roll* *yaw velocity* *lat. motion* *lat. velocity*	*1 degree* *0.3 degree/s* *0.7 m* *0.3 m/s*	*3 degrees* *1 degree/s* *2.2 m* *1 m/s*	*5 degrees* *1.5 degree/s* *3 m* *1.5 m/s*

Table 1. Seakeeping criteria

3. STABILIZATION PROCEDURES

3.1 Ship motions model with respect to control surfaces

The linear equations showing the ship behaviour for straight courses, at small angles and constant speed are expressed as:

$$(M + A_{22})\ddot{y} + (z_g M - A_{24})\ddot{\varphi} + A_{26}\ddot{\psi} + B_{22}\dot{y} - B_{24}\dot{\varphi} + B_{26}\dot{\psi} = F_y^g + F_y^d$$
$$(z_g M - A_{42})\ddot{y} + (I_4 + A_{44})\ddot{\varphi} - A_{46}\ddot{\psi} - B_{42}\dot{y} + B_{44}\dot{\varphi} - B_{46}\dot{\psi} + Mg(\rho - a)\varphi = M_\varphi^g + M_\varphi^d$$
$$A_{66}\ddot{y} - A_{64}\ddot{\varphi} + (A_{66} + I_6)\ddot{\psi} + B_{62}\dot{y} - B_{64}\dot{\varphi} + B_{66}\dot{\psi} = M_\psi^g + M_\psi^d$$

where:

F_i^g and M_i^g = forces and moments due to the different appendages
F_i^d and M_i^d = forces and moments due to disturbances
z_g = center of gravity z axis
M = ship mass
A_{ij} = added mass
B_{ij} = damping coefficient
I_i = inertia moment
$\rho - a$ = distance between the metacenter and the center of gravity

Each coefficient depends on the ship speed and the wave frequency range (ship encountered frequency with respect to the sea). At first, the numerical values have been derived from the Ship Motion Program (developed by the David Taylor Naval Research Center) which determines the ship behaviour by dividing it into many transverse strips and using a "finite elements" method. Subsequently, they have been identified and adjusted from sea tests on board a 1/12 scale model of the future NAC.

In these equations, the expression of the exerting forces and moments (by means of all the appendages including the active actuators) can be expressed, for a pair of appendages, as:

$$F_y^g = -\sum_{i=1}^{n} 2F_i \cos\gamma_i$$

$$M_{\varphi}^{g} = -\sum_{i=1}^{n} 2F_i d_i \cos\delta_i$$

$$M_{\varphi}^{g} = -\sum_{i=1}^{n} 2F_i x_i \cos\gamma_i$$

with

$$F_i = \frac{1}{2}\rho S_i V_i^2 C_{L\alpha} h_i \left(\beta_i + \frac{\dot{y} + x_i\dot{\psi}}{V_i}\cos\gamma_i + \frac{d_i\dot{\varphi}}{V_i}\cos\delta_i\right)$$

and where:

- β_i = control surface angle (zero for a passive appendage)
- S_i = surface of the actuator
- V_i = local speed modulus ($V_i \simeq V$)
- $C_{L\alpha}$ = lift coefficient
- h_i = coefficient of efficiency lost due to the hull
- x_i, y_i, z_i = coordinates of the control surface
- d_i = distance from the actuator center to the longitudinal axis $\left(d_i = \sqrt{y_i^2 + (z_i - z_g)^2}\right)$
- γ_i = slant angle with z axis
- ε_i = see figure 1 ($\varepsilon_i = atan(y_i/(z_i - zg))$)
- $\delta_i = \varepsilon_i - \gamma_i$

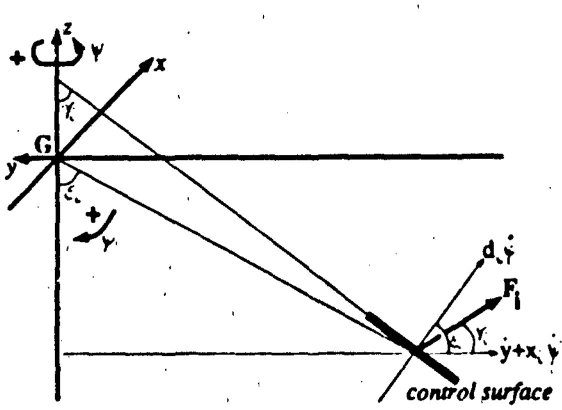

Figure 1. Magnitudes relating to the actuators

Rearranging the terms involving ship motions, these equations easily lead to the following matrix representation:

$$P\begin{pmatrix}\ddot{y}\\ \ddot{\varphi}\\ \ddot{\psi}\end{pmatrix} + Q\begin{pmatrix}\dot{y}\\ \dot{\varphi}\\ \dot{\psi}\end{pmatrix} + R\begin{pmatrix}y\\ \varphi\\ \psi\end{pmatrix} = T\begin{pmatrix}\beta_1\\ \beta_2\\ \beta_3\end{pmatrix} + T_d$$

where $\beta_1, \beta_2, \beta_3$ are linked to the active actuators and T_d is a disturbance vector.

Introducing the following state vector $\left(y\,\dot{y}\,\varphi\,\dot{\varphi}\,\psi\,\dot{\psi}\right)$, we can write the continuous state representation (1):

$$\begin{cases} \dot{x} = Ax + Bu + v \\ z = Cx + w \end{cases}$$

(v is a vector including all the disturbances not considered).

Thus, the whole operational constraints, previously described in the introduction, can be written in the form of a quadratic criterion of the type:

$$C = \sum_{k=1}^{N} \left(x_k^T \Lambda_2 x_k + u_k^T \Lambda_3 u_k \right)$$

where Λ_2 and Λ_3 are weighting matrices bound to the state vector and the control vector. A judicious choice of Λ_2 and Λ_3 can distribute on the state variables the different restrictions imposed to the ship motions.

As the process is discrete, we require the equivalent discrete state equations:

$$x_{k+1} = Fx_k + Gu_k + v_k$$

from the continuous system (1), with a sampling period T. Considering v_k as a white noise, we know that the infinite horizon optimal control minimizing the cost C is obtained for a steady system as follows:

$$u = -L_k \hat{x}_k$$

with

$$L_k = \left(\Lambda_3 + G^T S G\right)^{-1} G^T S F$$

where $\hat{x}_k$ is an estimate of the state at time k, knowing the whole observation $z_0, z_1, \ldots, z_k$. The matrix S is solution of the Riccati equation:

$$S = F^T S F - F^T S G \left(\Lambda_3 + G^T S G\right)^{-1} G^T S F + \Lambda_2$$

In a general way, with white gaussian noises (v and w), the estimated vector $\hat{x}_k$ can be obtained by a Kalman filter keeping the optimal nature of the complete scheme. So to be strict, and to preserve it, we should take into account in the state representation the dynamics induced by the wave efforts on the hull and the specific dynamics of the sea and wind. It means we need a model of these disturbances and an estimation in real time of the corresponding components of the state. If not, we will have a pseudo-optimal control because the state vector will not represent reality.

Moreover, it is important to consider that the deviations and the rates of the fins and rudders are restricted. Unfortunately, it is very difficult to deal with this kind of non-linear problem in respect to the models chosen for the control algorithms. So, in order to avoid the decrease in performances which occurs when saturation is reached, a method consists in adjusting the weighting matrix Λ_3 to stay in the linear working range of the actuators. Many statistical criteria permit the number of exceedings to be linked with the limit values. However, this procedure does not seem very judicious for different reasons. Indeed, this adjustment depends of course on the ship model and the spectral characteristics of the sea. So, we have two main consequences:

— sudden changes in the external conditions will require a new adjustment

— the inevitable model errors involve a sufficient security margin, which could lead to an under-employment of the actuators.

For all these reasons, it would be interesting to have an autonomous procedure permitting, in the one hand, the adjustment of the parameters and ensuring, on the other hand, to be under saturation.

3.2 Self-tuning linear quadratic control

This self-tuning approach can be outlined by splitting it into several successive steps:

0/ initialize control gains by integrating a steady state Riccati equation

then, at time t:

1/ estimate the risks of exceeding the maximum permissible angle and/or the maximum permissible rate of the actuators

2/ adjust the weighting matrices in terms of the proximity of saturation (defined in step 1)

3/ compute the recurrent solution of control gain calculations

Therefore, at time t, the question is to decide which parameters must be released (Λ_2, Λ_3 ?) and what rules must manage their possible variations. At first sight, we could think that setting both Λ_2 and Λ_3 free would put more room to manoeuvre at our disposal and would increase system sensitivity. However, as has been stressed by the initial tests carried out in this way, such freedom is bound to raise a number of insolvable problems:

— the terms of the matrix Λ_2, directly representative of constraints which we wish to assign to the ship motions, cannot be easily linked with saturation of the actuators.

— unless we keep the relative weight of every term in Λ_2 steady, we may distort in a progressive way the meaning of the selected initial criterion; otherwise, we cannot be sure to act as efficiently as possible on the motions involved by the criterion.

For all these reasons, it appears, finally, of little interest to modify the initial adjustment of the Λ_2 elements; this must keep its whole meaning which consists in defining for such or such a use the relative weight of ship motion stabilization.

However, by this very fact, there is no problem in determining the correlation rules between the terms of the matrix Λ_3 and the maximum angle or maximum rate of the actuators. The only remaining question concerns the way of moving these weightings in respect to real-time evolutions of the actuators. Many possibilities have been studied, but the main principle is schematized by the figure below (figure 2).

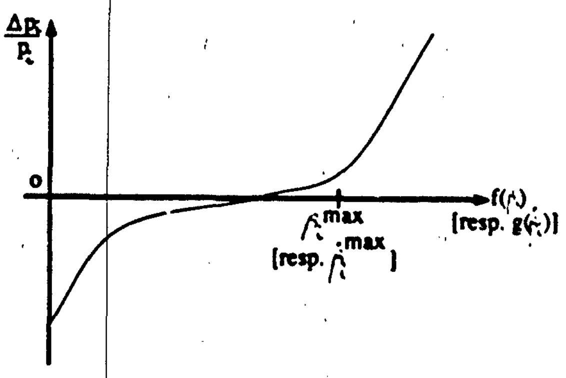

Figure 2. Principle of Λ_3 adjustment

p_i is the weighting factor of Λ_3 associated with the actuator i (maximum permissible angle β_i^{max} and maximum permissible rate $\dot{\beta}_i^{max}$) whereas $f(\beta_i)$ and $g\left(\dot{\beta}_i\right)$ are functions, to be adequately defined, of the trends of deflection and rate deflection.

The choice of $f(\beta_i), g\left(\dot{\beta}_i\right)$ is of course proving to be the crucial point as they will rule the process in terms of saturation risks or, on the contrary, of possible under-employment of the control surfaces. Moreover, there is no doubt it would be harmful to consider only the instantaneous values of angles β_i and velocities $\dot{\beta}_i$. Therefore, to increase process speed and stability, the choice finally turned to quantities stemming from a smoothing of predicted information on a given horizon. The following diagram (figure 3) summarizes steps 1 and 2.

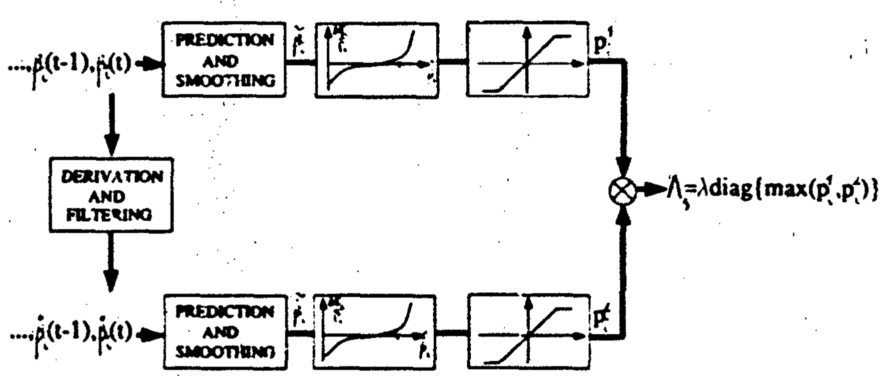

Figure 3. Complete self-tuning scheme

where λ is a factor permitting the adjustment of the algorithm adaptability.

From the so referenced Λ_3 matrix, it is necessary to find the new control gains. Because of computation time, we could not think of solving a Riccati equation at every iteration. Consequently, we shall be satisfied with computing it only once, at the initialization (step 0); then, we shall use the following recurrent equations:

$$L_k = \left(\Lambda_3^k + G^T S_{k-1} G\right)^{-1} G^T S_{k-1} F = K_k^T F$$

$$S_k^* = \left(I - K_k G^T\right) S_{k-1} \left(I - K_k G^T\right)^T + K_k \Lambda_3^k K_k^T$$

$$S_k = F^T S_k^* F + \Lambda_2^k$$

To prove this recurrent solution, Λ_3 dynamics of change must obviously be much slower than computation dynamics.

4. HEEL COMPENSATION

In addition to the stabilization problems for sway, roll and yaw motions, another specification of the S.A.T.R.A.P. system concerns heel cancellation. This could be carried out by means of the anti-rolling fins or water ballasting in the tanks indifferently. Nevertheless, we shall mainly use the tanks for many reasons:

— full efficiency of the fins must be preserved to control high frequency motions

— at low frequencies, the fins are less effective so that their use would lead to a steady state of saturation without sufficient decrease of the heel

— unlike the control surfaces, the capacity of the water tanks is independent of ship speed

The heel is a low frequency motion induced by two main causes: external disturbances (motions on the flight-deck, wind, etc...) and specific vessel dynamics (gyration, change of course, etc...). It leads us to separate the heel compensation problems in straight courses from those in gyrations.

4.1 Heel elimination in straight course

As has been previously stressed, the stabilization model results from small angle modeling, at constant speed, which does not take into account low frequency motions. That is one of the reasons why the heel compensation loop was not included in a global multivariable control.

Having no on-board specific heel sensor at our disposal, the only way to restore it involves observations of the roll and actuator deflections. These measurements will be filtered to keep only the low frequency part and then properly mixed, leading to the water mass to be transferred as:

$$M(\rho - a)\sin\bar{\varphi} + C(\bar{\alpha}) = md\cos\bar{\varphi}$$

where

$\bar{\varphi}$ is the filtered value of the roll
$\bar{\alpha}$ is the filtered value of the fin deflections
$C(\bar{\alpha})$ is the roll moment induced by the fins (cf figure 5 for the graphs of theoretical efficiency)
m is the water mass to ballast
d is the lever arm associated with a pair of tanks

The result is the following complete diagram (figure 4):

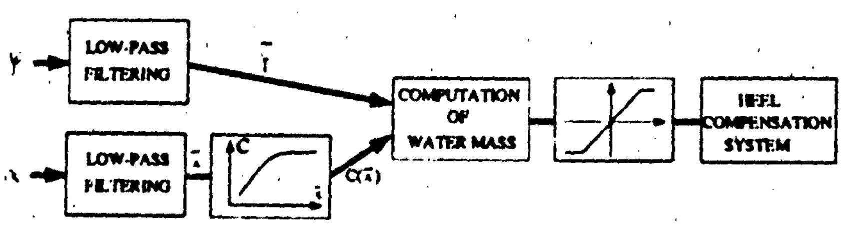

Figure 4. Heel elimination in straight course

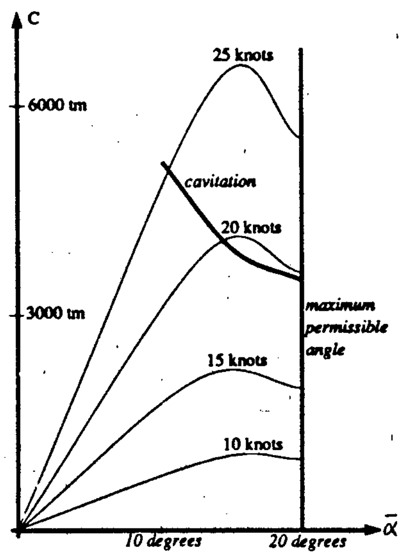

Figure 5. Roll moment induced by fin angles

This autonomous procedure could be permanently operating and will cancel the heel in a progressive way.

4.2 Heel elimination in gyration

The main purpose considered to this point consists in allowing the ship to reach a new course as quickly as possible, without attaching the planes to the flight deck. Consequently, the maximum permissible heel will have to be kept below one degree. In view of the water ballasting dynamics (long response times and delays) and the lag inherent in heel estimation, it proves, firstly, to be impossible to drive the pumps in real time. It is, therefore, essential to pre-record (in batch mode) the computation of the whole series of water ballasting providing a minimum heel during gyration. This "open loop" type operation will obviously be completed by a "closed loop" action of other actuators (fins and rudders). It requires modeling, even simplified, for heel motions of the ship in gyration, also including wind effect modeling.

4.2.1 Ship model

It is of the traditional manoeuvrability modeling type; therefore, it requires a string of adimensional hydrodynamic coefficients which have been gradually perfected by the Bassin d'Essais des Carenes, from real tests (cf §6) at different speeds. The model comes in the following form, which brings out a state vector $\left(\varphi\, \dot{\varphi}\, \psi\, \dot{\psi}\, u\, v\right)$, where u and v are the components

of the speed vector projected onto the ship reference system :

$$
\begin{aligned}
(\mu + \mu_1)\,\dot{u} = {} & \mu v r - \mu z_g \dot{\varphi} r + \frac{1}{\rho W}\left(A_x + X_s + R\right) \\
& + \frac{V^2}{2kL}\left(C_{x_0} + C_{x_{vr}} v^* r^* + C_{x_{r^2}} r^{*^2}\right) \\
& + \frac{V^2}{2kL}\left(C_{x_{v^2}} v^{*^2} + C_{x_{\alpha^2}} \alpha^2 + C_{x_{r\alpha}} r^* \alpha\right)
\end{aligned}
$$

$$
\begin{aligned}
(\mu + \mu_2)\,\dot{v} - \mu z_g \ddot{\varphi} = {} & -\mu u r + \frac{1}{\rho W}\left(A_y + Y_s\right) + \frac{V^2}{2kL}\left(C_{y_v} v^* + C_{y_r} r^*\right) \\
& + \frac{V^2}{2kL}\left(C_{y_\alpha} \alpha + C_{y_{r\varphi}} |r^*| \varphi + C_{y_{\Delta l\alpha}} (v^* + \mu r^*)^2 \alpha\right) \\
& + \frac{V^2}{2kL}\left(C_{y_{\Delta l^2}} (v^* + \lambda r^*)\,|v^* + \lambda r^*| + C_{y_{\Delta l^3}} (v^* + \lambda r^*)^3\right)
\end{aligned}
$$

$$
\begin{aligned}
L^2 (\lambda_1 + \chi_1)\,\ddot{\varphi} - \mu z_g \dot{v} = {} & \mu z_g u r - \mu g f(\varphi) \sin(\varphi) + \frac{1}{\rho W}\left(A_l + L_s + Q + M_c\right) \\
& + \frac{V^2}{2k}\left(C_{l_v} v^* + C_{l_r} r^* + C_{l_\alpha} \alpha + C_{l_p} \dot{\varphi}^* + C_{l_\varphi} \varphi + C_{l_{\varphi^3}} \varphi^3\right)
\end{aligned}
$$

$$
\begin{aligned}
L^2 (\lambda_3 + \chi_3)\,\dot{r} = {} & \frac{1}{\rho W}\left(A_n + N_s\right) + \frac{V^2}{2k}\left(C_{n_v} v^* + C_{n_r} r^* + C_{n_p} \dot{\varphi}^*\right) \\
& + \frac{V^2}{2k}\left(C_{n_\alpha} \alpha + C_{n_{r\varphi}} |r^*| \varphi + C_{n_{\Delta l^2}} (v^* + \nu r^*)\,|v^* + \nu r^*|\right) \\
& + \frac{V^2}{2k}\left(C_{n_{\Delta l^3}} (v^* + \nu r^*)^3 + C_{n_{\Delta l\alpha}} (v^* + \mu r^*)^2 \alpha\right)
\end{aligned}
$$

with:

$\dot{\psi} = r \cos\varphi$; $v^* = \frac{v}{V}$; $u^* = \frac{u}{V}$; $\dot{\varphi}^* = \frac{L\dot{\varphi}}{V}$; $r^* = \frac{Lr}{V}$
$V = \sqrt{u^2 + v^2}$ (ship speed)
$\mu = 1$ (normalized ship mass)
$\chi_1 = \frac{I_4}{\rho W L^2}$; $\chi_3 = \frac{I_6}{\rho W L^2}$ (inertia moment coefficients)
$\mu_1 = \frac{A_{11}}{\rho W}$; $\mu_2 = \frac{A_{22}}{\rho W}$ (added mass coefficients)
$\lambda_1 = \frac{A_{44}}{\rho W L^2}$; $\lambda_3 = \frac{A_{66}}{\rho W L^2}$ (added inertia coefficients)
ρW = vessel displacement
$k = \frac{W}{AL}$ (A : projected vertical area , L : ship length)
$f(\varphi) = \rho - a$ (depends on the heel because of poseidons)
z_g = ordinate of CG (linked with the reference system chosen to project equations)
λ, μ, ν = constants
A_x, A_y, A_l, A_n = components of the whole aerodynamical force
X_s, Y_s, L_s, N_s = components of the force due to the fins
$M_c = 4\rho g d V_e \cos\varphi$ (moment for water ballasting with two pairs of tanks)
V_e = volume of water to be transferred

Q, R = force and moment exerted on the ship by the propellers and computed as:

$$J = \frac{(1-\sigma)\,u}{nD}\left(1 + a\,(v^* + \mu r^*) + b\,(v^* + \mu r^*)^2\right)$$

where

σ = suction coefficient
D = diameter of propeller
n = number of revolutions of propeller
a, b = constants

and then:

$$Q = \begin{cases} 2\rho n^2 D^5 K_1(J) & , \; if \;\; |J| \leq 1 \\ 2\rho u^2 D^3 C_1(1/J) & , \; if \;\; |J| \geq 1 \end{cases}$$

$$R = \begin{cases} 2\rho n^2 D^4 K_2(J) & , \; if \;\; |J| \leq 1 \\ 2\rho u^2 D^2 C_2(1/J) & , \; if \;\; |J| \geq 1 \end{cases}$$

4.2.2 Wind modeling

Wind effects modeling has been enabled by gathering experimental and theoretical approaches. At first, in view of the difficulty of performing aerodynamic measurements at full scale, a set of tests on scale model was carried out at the Bassin d'Essais des Carenes. The wind was simulated by means of a bank of fans. It permitted the measurement of the steady heel of the ship in response to different winds, of varying heading and speed. With the help of the stability graph, the associated heeling moments have thus been inferred (A_l). Figure 6 shows some corresponding test results.

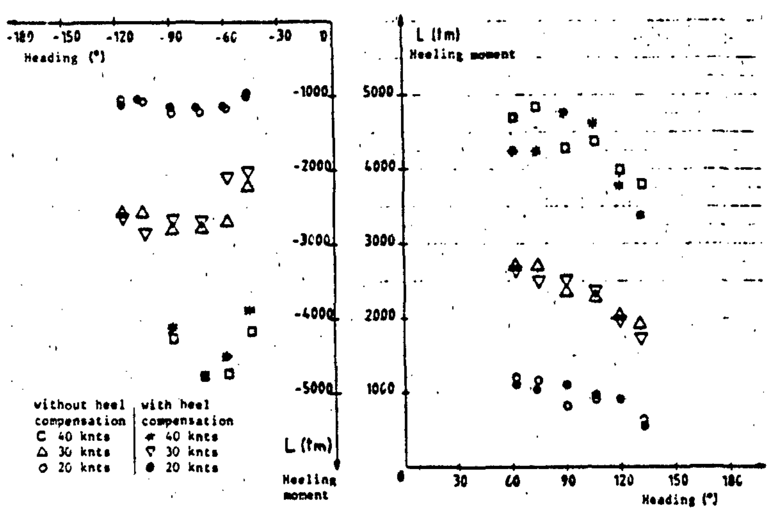

Figure 6. Induced roll in respect to the wind heading

Wind effects on other axes (A_x, A_y, A_n) being much less easy to estimate experimentally, they have been modeled by the theoretical computation of the N.A.C. aerodynamic coefficients (Isherwood method).

4.2.3 Heel compensation methodology

Using all the previously described modeling, it is, therefore, possible to realize an initial simulation, within a given range (course to reach, ship speed, wind force and heading features), giving a heel curve without compensation (cf figure 7).

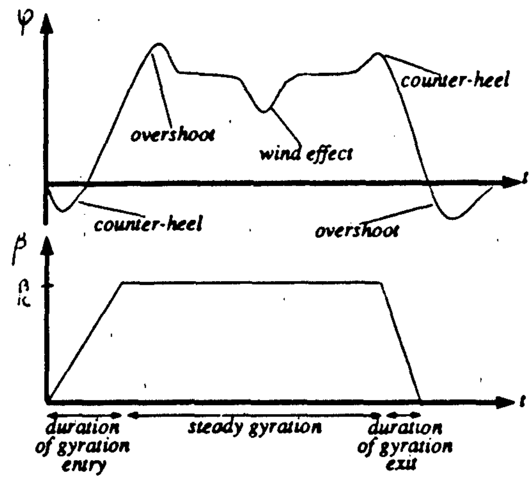

Figure 7. Parameters acting on the heel variations

The aims are triple:

— to reach the new course

— to turn in minimum time

— to keep the heel below one degree

From this, a number of parameters seem to be decisive:

— the rudder angle, which must allow the N.A.C. to turn as quickly as possible whilst remaining within the limit of tank stabilizing capacity

— the duration of steady gyration determined by the course to reach

— the durations of gyration entry and exit, permitting the adjustment of the pump dynamics to ship dynamics

— the commutation times, the water mass to transfer and the pump outflows to minimize the heel

With such a schedule of conditions (simulation modeling + criterion to minimize + list of unknown but specified parameters), it is obvious that the problem can be solved with an optimization procedure; indeed, it is impossible to find a simple analytical solution. With this in mind, two stages have been developed. The first allows the definition of a good initialization of the parameters, using an iterative logic. The second improves the results by means of a non-linear programing method.

Otherwise, despite of the care exercised in modeling all the phenomena, many noticeable divergences may occur during gyration (particularly in respect to the heading changes predicted in simulation). In order to keep the appropriateness between the pre-recorded water ballasting and the turning of the ship, it proved to be essential to compel the ship not to move from the conditions of the simulation. It has been achieved by introducing the notion of "reference trajectory", which means that the heading changes are slaved to those a priori defined by the pre-recorded simulation. Considering, for instance, a control law of proportional-derivative type, rudder deflection could be written as:

$$\beta = \beta_c + k_1 \left(\psi(t) - \psi_{ref}(t)\right) + k_2 \left(\dot{\psi}(t) - \dot{\psi}_{ref}(t)\right)$$

where β_c is the nominal deflection for the studied gyration and $\psi_{ref}(t), \dot{\psi}_{ref}(t)$ represents the heading change (and rate of change) predicted by the pre-recorded simulation.

Finally, the elimination of high frequency disturbances (modeling inaccuracy, residual errors, swell) will be realized by the means of fins.

5. FREE MODEL OF THE NUCLEAR AIRCRAFT CARRIER

To test the validity of the system S.A.T.R.A.P., the D.C.N./S.T.C.A.N. (Department of Naval Construction, linked to the French Government) has decided to build a free model, the research, construction and operation of which were entrusted to the Bassin d'Essais des Carenes. Thus, the first problem to be solved was to specify the scale of such a model. The main constraints were that the ship had to be as large as possible (to minimize scale effects) and to be able to accomodate the test crew. The choice was thus the result of a compromise between:

— measurable sea conditions

— minimum dimensions necessary for the crew

— effects of scale on mass and inertia

— manufacturing costs

Finally, after many studies, the scale 1/12th was chosen for the free model.

The sea tests started on October 1987, and they allowed experiments such as:

— assessing the performances of the ship in calm and high sea state conditions

— calculating the dimensions of the components used in the final system (power units, fins and rudders efficiency, on-board sensors...)

— simulating various failures and breakdowns

to be carried out.

The main characteristics of this model are described in the table 2;

overall length	*21.9 m*
length between perpendiculars	*19.8 m*
waterline width	*2.6 m*
overall width	*5.5 m*
level of flight deck to baseline	*2 m*
displacement	*20 t*
maximum speed	*9 knots*
draught	*0.7 m*
GM	*0.17m*
power on board	*110 kva*
available propeller power	*2x20 kw*
shaft speed	*530 rpm*
material	*light alloy*

Table 2. Some values concerning the free model

In respect to sensors, more than 64 input channels are arranged throughout the free model in order to record, at the 20 Hz frequency, the ship position (motions, velocities, external conditions ,etc...) and work parameter measurements (engine speeds, hull speeds). The on-board system consists of a computer managing the input signal and producing control system and automatic steadying commands for the deck (sampling period for the control laws = 0.1 s). It consists of a 256 input-channel processor, a system to transfer data to a land-based information center, and several peripheral devices.

Table 3 gives the fin and rudder characteristics, at full scale of N.A.C.;

Installation	*Comprising*	*Features*	*Power used*
Steering sub-system	*two independent cross-head rudders*	*unit surface =19m2 angular speed =10 deg/s*	*< 200 kW*
Stabilization sub-system	*four independent flap fins*	*unit surface =12m2 angular speed =10 deg/s*	*< 400 kW*
Heel compensation sub-system	*two independent pairs of tanks*	*max. water ballasting =2x45t transfer speed =1.5t/s*	*< 500 kW*

Table 3. Fin and rudder characteristics

To summarize, figure 8 shows a transversal section view of the free model, situating all the on-board equipment.

Finally, the re-arrangement of the signals and the reconstitution of the complete state vector involved by the algorithms are schematized by the diagram below (figure 9);

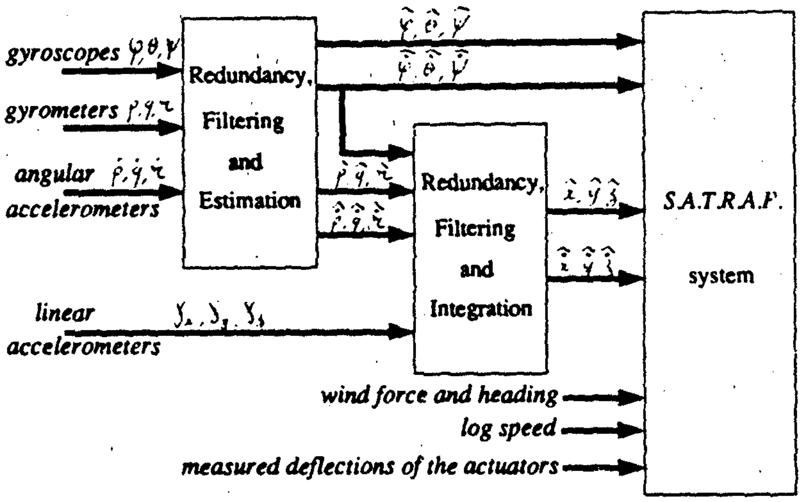

Figure 9. Measurement filtering and state estimation

6. TEST RESULTS

The free model of the N.A.C. permitted the validation and improvement of all the procedures which have been decided. In a first stage, it has been used to adjust the different models previously described (stabilization and gyration). Figure 10 shows an example of model identification (cf § 3.1) by using a sweep excitation signal to drive the rudders. Parameter estimation is computed with a temporal method based on an output error criterion. This kind of test is rather delicate to implement as it requires:

— keeping an almost constant heading throughout the test duration
— having, nevertheless, an excitation signal sufficiently rich to allow significant parameter adjustment
— very favourable sea conditions (good signal/noise ratio)

With regard to the control laws, the different operational constraints have been expressed in the form of quadratic criteria using state vector components. For obvious course keeping considerations, the yaw must always appear in the weighting list. Among the remaining degrees of freedom, roll and sway cannot be easily controlled together. In that view, the stabilization of motions for specific ship points should result from a compromise between the different goals involved.

Figures 11 and 12 introduce two examples of this criterion use to limit motions. In the first, only the roll and yaw motions are weighted; in the second, sway is in addition taken account from time t=180s. The roll actually appears not so well reduced, in aid of the sway.

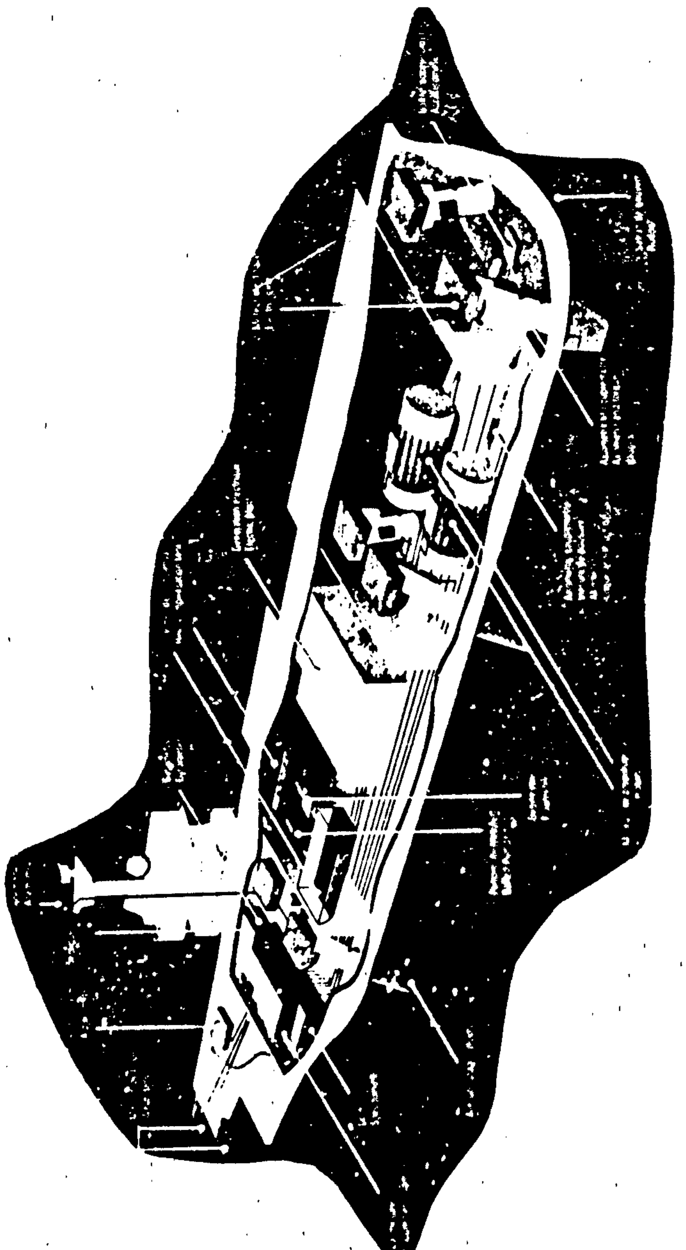

Figure 8. Section view of the free model

For both tests, the water ballasting operation will be noticed during the first minute (cf § 4.1), fin deflection beginning afterwards.

To summarize, all the tests showed the possibility of reducing quite well the roll motion while ensuring course keeping. Otherwise, they confirmed the difficulty of stabilizing lateral motions and velocities, which was sensed throughout the initial feasibility study.

About the heel compensation during gyration, the real time procedure has been implemented on board the free model, and successfully experimented. The data base, compiled from the batch optimization, had been computed in advance in the laboratory, so that a large and sufficient range of winds (heading and force sweeping) was covered. For greater convenience in implementation, the reference trajectory was always associated with a null wind, which means a quite restricting assumption.

Two examples of gyration are displayed in figures 13 and 14; these are 180 degrees turning, respectively carried out at 4.33 and 5.77 knots (15 and 20 knots at full scale) with nominal rudder deflections of —10 degrees and +15 degrees. These figures, which give the theoretical results predicted by the initial simulation (batch optimization of water ballasting), are respectively linked with rear wind (4 knots) and wind on the beam (14 knots) in respect to the initial heading of the vessel before turning. In practice, at the time of the associated tests (figures 15 and 16), it is unhappily difficult to rely on steady established winds, especially at the scale model. For instance, during the test shown in figure 16, the actual wind fluctuated between 10 and 20 knots. For that reason, in view of the difficult conditions encountered (high sea state and equivalent wind near 100 kms/h at full scale), the results appear very encouraging as far as procedure robustness is concerned.

7. REFERENCES

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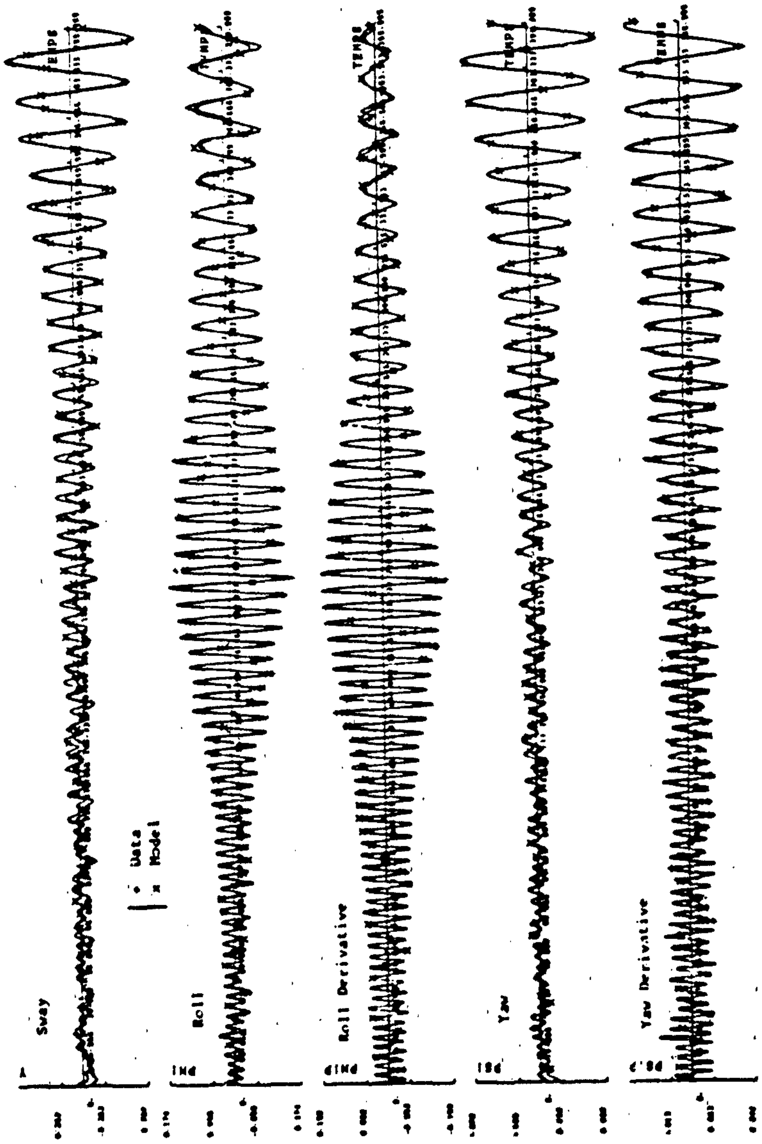

Figure 10. Model identification with sweep excitation

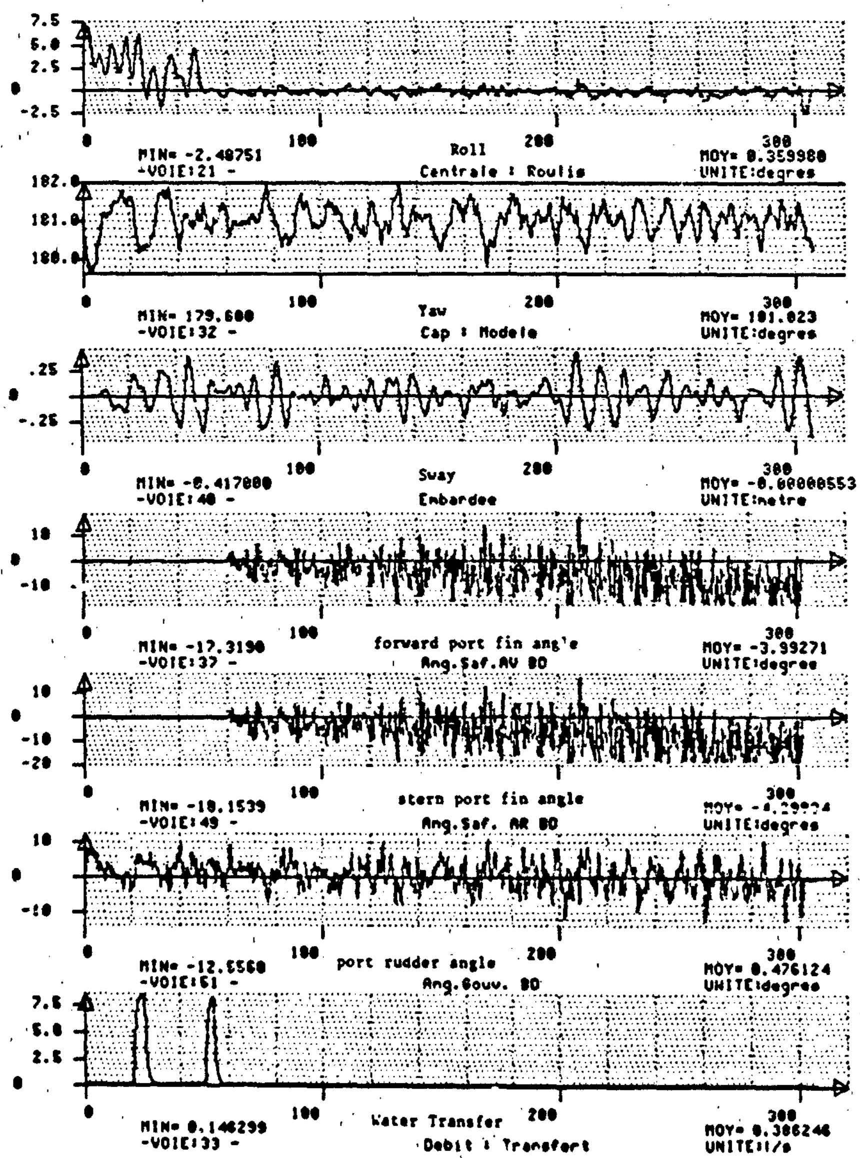

Figure 11. Roll and yaw weighting

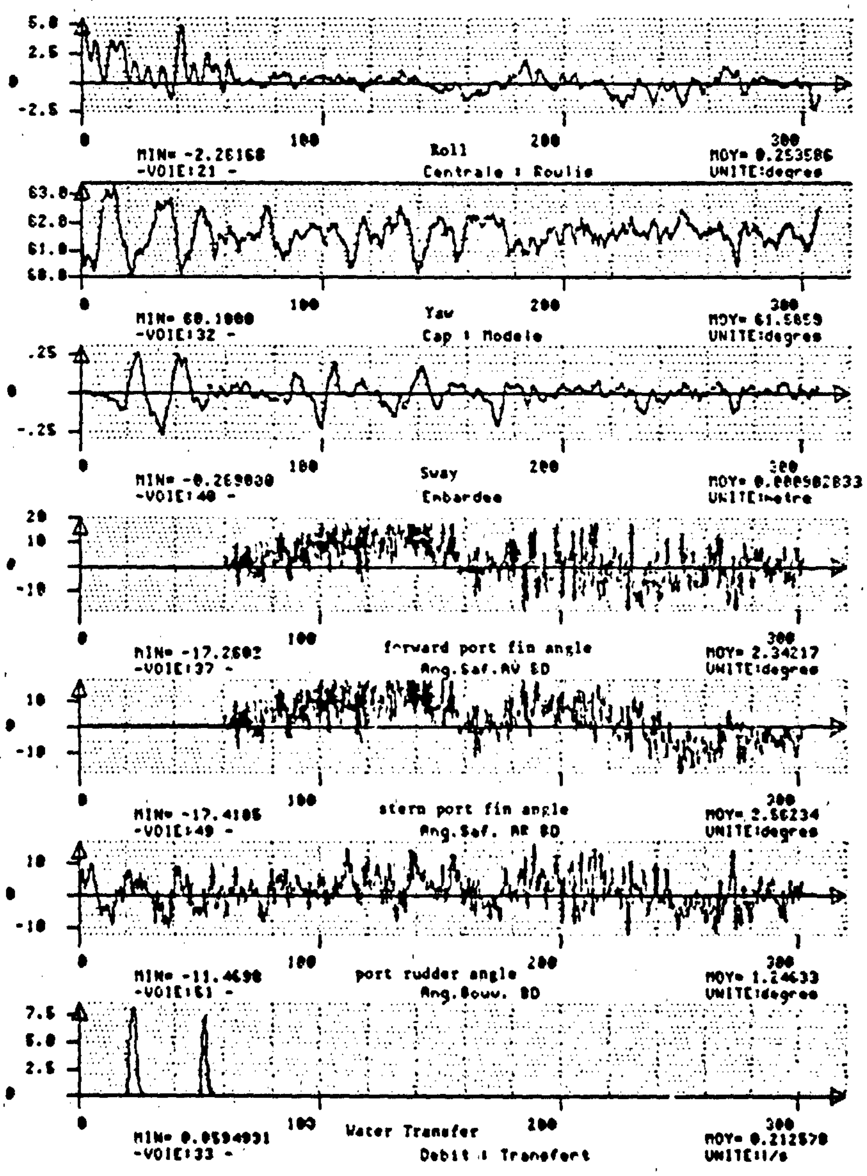

Figure 12. ***Roll, yaw and sway weighting***

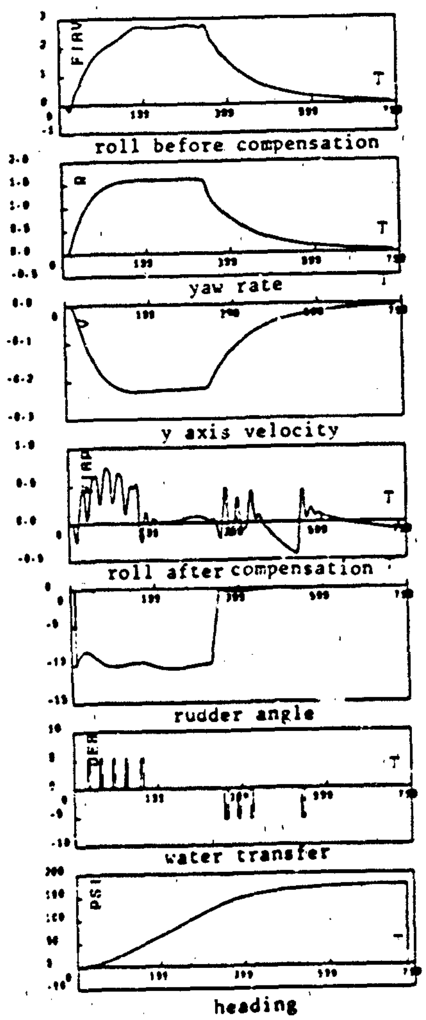

Figure 13. Simulation of a gyration with rear wind

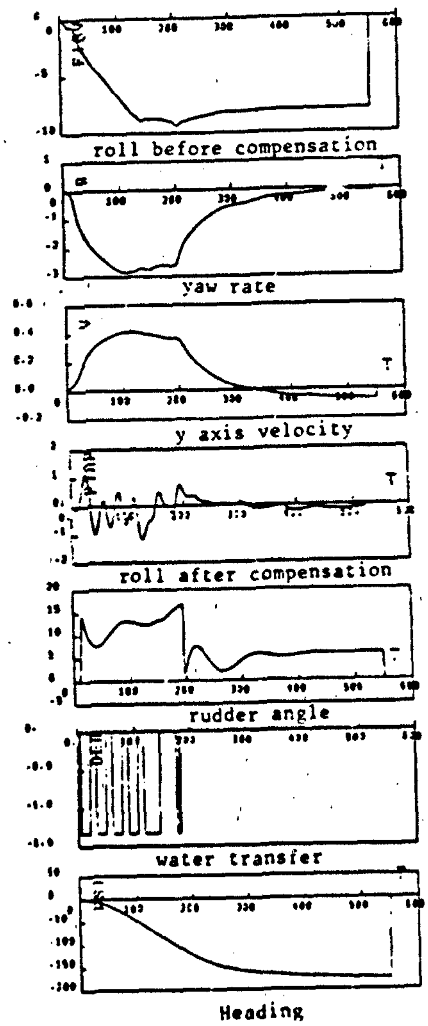

Figure 14. Simulation of a gyration with wind on the beam

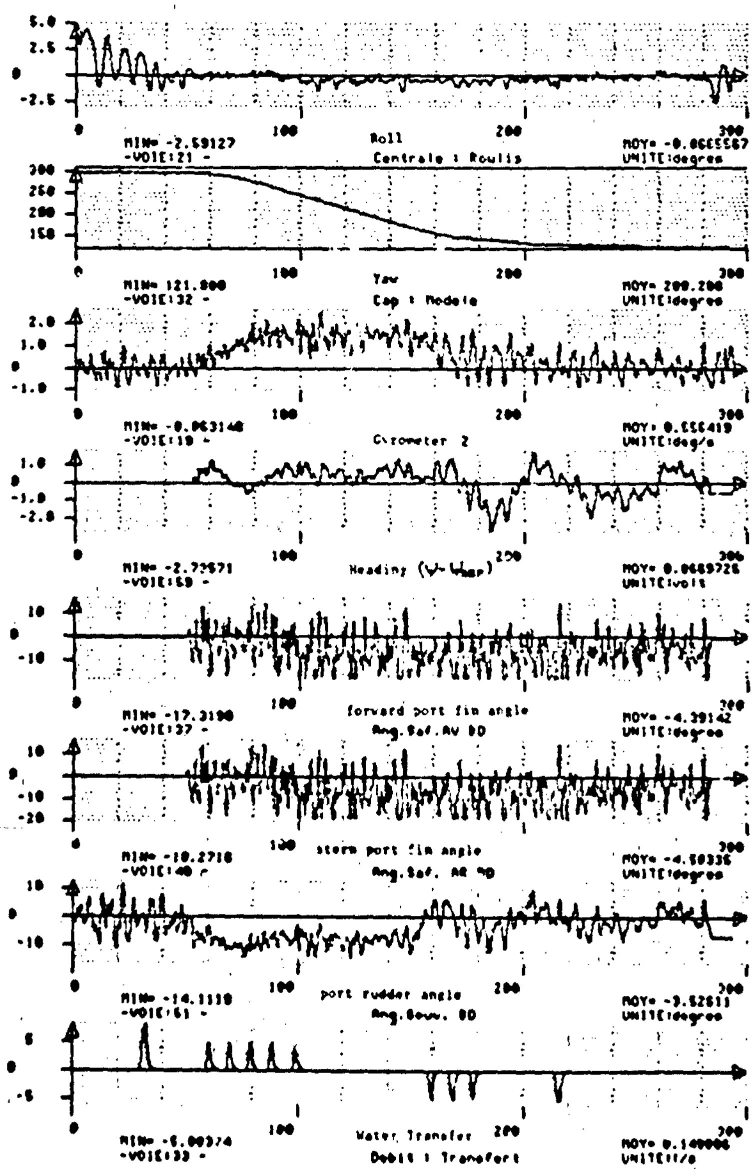

Figure 15. Test of a gyration with rear wind

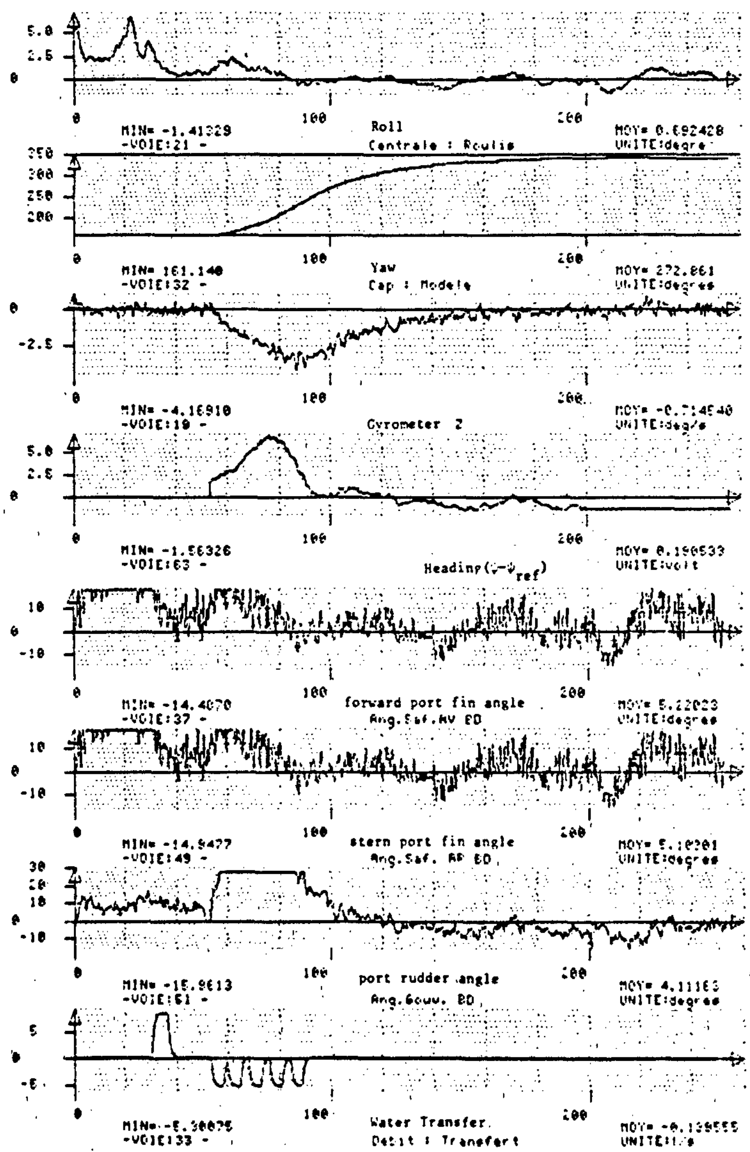

Figure 16. *Test of a gyration with wind on the beam*

CONTROL OF WHOLE SHIP PLATFORM STABILIZATION

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1. ABSTRACT

This paper addresses the most recent development of the application of modern digital control technology to the control problems associated with the task of whole ship platform stabilization.

There are several techniques available to dampen the roll of a ship and some may be optimised by the use of these modern digital technologies. In addition, some vessels may require the use of more than one roll damping technique to enable effective roll damping in a variety of situations.

The paper is therefore a review of the techniques available, their performance, relative cost effectiveness, and discusses their suitability for a range of operational profiles.

2. INTRODUCTION

There have been multitudes of ingenious devices produced for stabilizing ships since the early days of power driven vessels, all of which are well documented elsewhere. From this work, three main types of active system have emerged:

- Tanks - operating by transfer of ballast
- Moving Weight
- Fins - dedicated stabilizer fins and rudders

Passive systems, those which have no power input or external control (eg bilge keels, static tanks), have not been considered here because generally their performance in non ideal conditions is disappointing.

The discussion of the various stabilizer systems under review will be based upon a typical frigate whose dimensions are:

LOA	120 m
Displacement	3300 tonnes
Beam	13.5 m
Metacentric Height	1.3 m

Roll Period	11 seconds
Design Speed	20 knots
Maximum Speed	30 knots
Wave Slope Capacity	3 degrees
Stabilizing Moment	2200 KNm

The Wave Slope Capacity is the moment required to statically roll the vessel to 3 degrees. This is generally accepted as a measure of the power available from the stabilizer system. The 3 degree Wave Slope capacity used for this example is typical of the power installed on warships using active fins.

Moment = Displacement x Metacentric Height x Sin 3 degree (Wave Slope Capacity)

= 3300 x 1.3 x 0.0523 x g KNm

= 2200 KNm

Consideration will be given to three main areas:

- Effective stabilizers for low ship speeds
- Cost effective stabilization over a range of ship speeds
- Benefits of Digital Control

The performance standard for comparison will be the active fin stabilizer fitted to a typical frigate.

Mine counter measures vessels, offshore patrol vessels and hydrographic survey vessels could all benefit from a successful stabilizer operating at low ship speeds. Very few have such equipment at present and the reasons for this state of affairs will be examined.

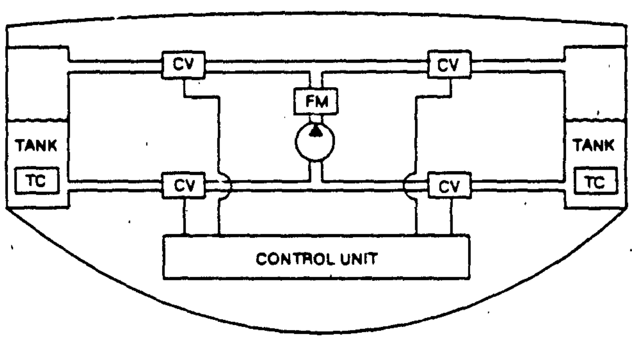
SWATH vessels, by virtue of their very low waterplane area, provide new horizons for the control of ship motions and modern digital controllers can provide the control solutions for pitch heave and roll. For simplicity the comparison of the various systems will only be made with reference to the typical frigate in order to give a picture of the relative merits of each type.

3. STABILIZER SYSTEMS

3.1 Tank System

Tank systems have found some applications on commercial vessels, but have not been favoured where space is at a premium. Most existing types are passive, or with some degree of control over the water flow by throttling the air passages between tanks. A fully active system with ballast transfer pumps would be required to provide the level of performance defined for the typical frigate. This performance level (3 degree WSC) is the standard considered necessary for adequate stabilization, practical experience having shown that a lower WSC is not perceived to be satisfactory.

The transfer pump will be run continuously at constant speed. In the standby condition suction may be taken from either tank and delivery returned to the same tank. When the control system demands a transfer of ballast the control valves will be positioned to open the relevant suction and delivery pipes to meet the demand. The control system will be provided with information concerning the contents of each tank, flow rate between tanks and the position of each control valve. (Fig 1).



TRANSFER PUMP
CV CONTROL VALVE
FM FLOW METER
TC TANK CONTENT SENSOR

Figure 1 - Hull Section - Tank System Block Diagram

To provide the desired moment for stabilization, a mass of 19.5 tonnes is required at an arm of 5.75m. The target time to match fin stabilizer performance is .166 of the vessel's roll period, for a complete reversal of stabilizing moment.

$$\text{Pumping Rate} = \frac{\text{Mass}}{11 \times .166}$$

$$= \frac{39.0}{1.83}$$

$$= 21.3 \text{ tonnes/sec}$$

A flow rate of 21.3 tonnes/sec is clearly a very large requirement which would probably be impractical in most situations.

Pumps readily available today are limited to well below this capacity and some 600 KW would be required as a peak power input.

The control system for the active tank stabilizer regulates the flow of water between tanks in order to maintain a differential mass each side of the vessel in opposition to the rolling motion.

The control system comprises sensors to measure roll angle and rate, plus tank water level and flow rate sensors. These inputs are processed to generate signals to drive the four water flow control valves.

The basic control strategy for the system is:

$$\Delta Md = a_0\theta + a_1\dot{\theta} + b_0\Delta Ma + b_1\Delta\dot{M}a$$

Where ... i is the required difference in mass between port and ..arboard tanks

... is the ship's roll angle

... s the ship's roll rate

ΔMa is the actual difference in tank mass

$\Delta\dot{M}a$ is the mass transfer rate

a_0, a_1, b_0 and b_1 are coefficients

The above control algorithm may be satisfactorily implemented using analogue techniques and as a stand alone stabilization system, the ballast tank cannot be greatly improved by the implementation of digital control. However, in the case of an integrated steering-stabilizer system, the tanks could be effectively employed to minimise heel in turns by feeding forward rudder angle and ship's speed and using these, via a digital precompensation algorithm (Ref 1), to anticipate and correct rudder induced roll.

To summarise, an effective system will need:

- $38m^3$ tanks port and starboard, at the shipside
- 55 tonnes added weight
- 600 KW peak power

Although this system is technically feasible its impact on space and power consumption is large. The main attraction of the system is its effectiveness at any ship speed, particularly low speeds, in applications such as survey vessels or minehunters where the ship is operating below the speeds at which fin stabilizers would be effective. Reductions in performance and consequent reduction in space, weight and power could be made, so that adequate performance in conjunction with fin stabilizers would be achieved. The cost of this combination may be prohibitive.

3.2 Moving Weight System

Feasibility studies conducted by VT to date (Ref 2) have been based upon an 8 tonne mass, so to provide the necessary stabilizing moment for our

typical frigate, a minimum of 4 units would be required. To scale up the design will require hydraulic system components which are not readily available in commercial size ranges, so multiple systems will be essential. To provide the desired moment for stabilization a mass of 39 tonnes is required at an arm of 5.75 m.

The mechanical design consists of a weight mounted on a flat athwartship steel track and attached to an endless flat belt which is looped around one driving pulley and one idler pulley fabricated to each end of the track. (Figs 2 and 3).

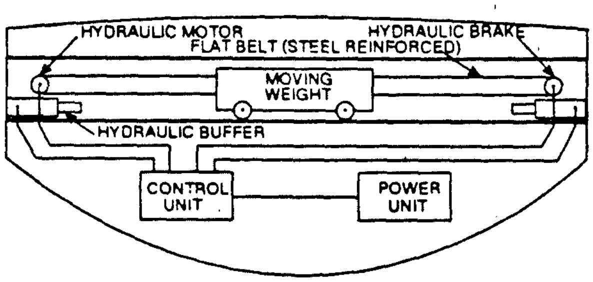


Figure 2 - Hull Section - Moving Weight Installation

With a controlled moving weight system the hydraulic drive system can be designed to extract energy from the motion of the weight. By the use of accumulators some potential energy of the weight can be stored and used to provide the accelerating force elsewhere in the duty cycle. Excess energy is dissipated as heat. These accumulators are initially charged from a make-up pump, and thereafter no further energy input is required from the ship's generators. Shock absorbers at each end of the track and capable of stopping the weight at its maximum speed.

The regenerative moving weight control system design study conducted by Vosper Thornycroft and Glasgow University concluded that bang-bang (on-off) control gave the best RMS roll reduction whilst maintaining a positive energy balance in the system. The resulting control strategy was of the form:

$$Fw = F1.SIGN(b_1\dot{\theta} + b_2\ddot{\theta} - a_0\xi - a_1\xi)$$

Subject to the constraints: If $|\xi| > |\xi|_{max}$ $Fw = 0$

If $\xi > \xi_{max}$ $Fw = 0$

Where: Fw is the force exerted on the weight

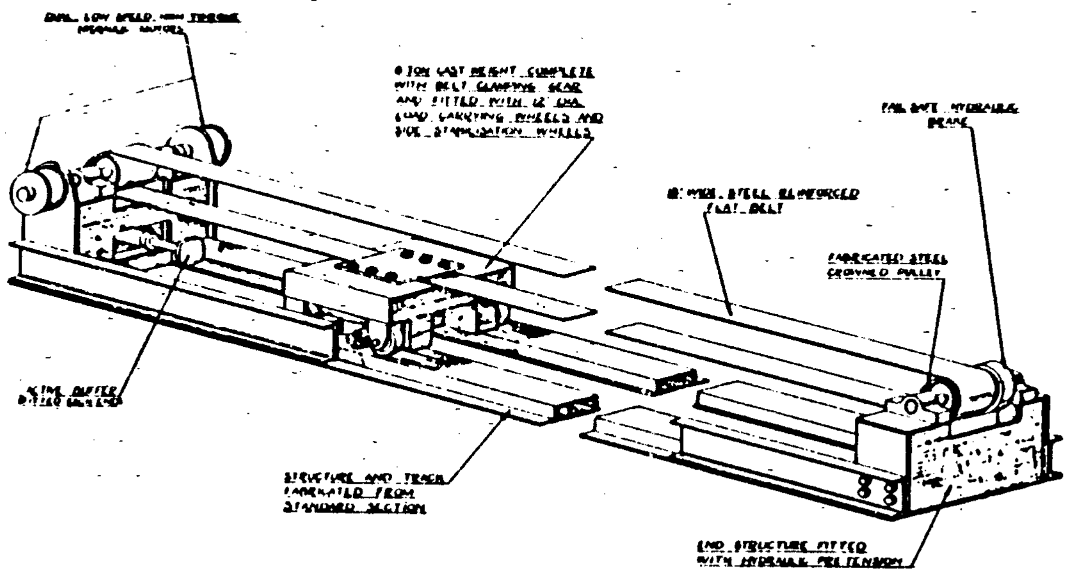


FIG 3. MOVING WEIGHT STABILIZER

Pl is the available power in the drive

$\dot{\theta}$ is roll rate

$\ddot{\theta}$ is roll acceleration

ξ is the weight position about the centre line

$\dot{\xi}$ is the weight velocity

b_1, b_2, a_0, a_1 are coefficients

Whilst the algorithm could be implemented digitally, this would offer no significant performance improvement over the analogue equivalent except that, as in the case of the water ballast system, it would be possible to introduce a precompensator to minimise rudder induced roll.

A more interesting possibility for this algorithm, by virtue of its on-off nature and the constraints on weight motion, would be implementation via a fuzzy logic controller, using rules for each of the four roll and weight motion terms. The benefits of fuzzy logic for control applications are described in Ref 3.

The moving weight system offers considerable advantages over ballast tanks in terms of energy consumption, whilst offering similar stabilization performance. The practical engineering problems could all be solved, leaving this system as one of the best solutions to date for a low ship speed stabilizers.

However, there are large energy transfers to be achieved, and weight control in damage and emergency conditions has to be addressed. (Ref 2).

The system will need:

- 70 tonnes added weight
- $92m^3$ space running the full width of the vessel

3.3 Rudder Roll System

The whole question of using rudders as stabilizers has been covered in great detail elsewhere by several researchers (Ref 4). The main factors emerging from the research data and documented trials are as follows:

- Rudder rate must be increased to 8 degrees/sec
- Rudder area should be increased to give improved performance
- Roll stabilization does not approach the 3 degree VSC level, mainly due to the limits imposed by the yaw and roll bandwidth separation

Rudder roll stabilization relies upon the frequency separation of the rudder-yaw and rudder-roll responses, by using fast rudder motion to suppress

rolling whilst moving the rudder more slowly to generate yaw for heading control.

The most successful RRS controllers have been designed using modern control theory and are adaptive in nature. Kalman filtering techniques are used to extract roll motion signals from a rate sensor output. The controllers, which normally include an autopilot, rely on the power of current generation microprocessors to execute the complex adaptive algorithms.

The generalised control strategy for a rudder roll autopilot system is:

$$\delta c = a_0\theta + a_1\dot{\theta} + b_0\gamma + b_1\dot{\gamma}$$

where δc is the rudder command angle

θ is the ship's roll angle

$\dot{\theta}$ is the ship's roll rate

γ is the ship's yaw angle

$\dot{\gamma}$ is the ship's yaw rate

a_0, a_1, b_0, b_1 are determined by the adaptive algorithm.

RRS is the only type of stabilization currently in service for which digital techniques have proved essential for satisfactory operation.

A benefit of RRS is that the controller can use existing communications between the steering position and steering gear, so that no other control modifications are required to install the system, thus if the controller is switched off, or fails, it may be bypassed and the steering function is not affected.

In addition to conventional steering and autopilot modes the rudder roll system provides:

(1) Stabilization On
Autopilot Off

The rudder demand signals from the helmsman are modified to provide a steering and roll stabilization demand on the rudder.

(2) Stabilization On
Autopilot On

The system provides a course keeping ability and roll stabilization.

The modern classes of vessel with purpose built controllers are the Danish Stanflex 300 and the Dutch 'M' Class. In addition, the Swedish 'Roll Nix' controller which is available commercially, and is already installed on a significant number of ships.

These three controllers represent the state of the art in control, but the stabilization performance relies heavily on the selection of ideal vessels exhibiting large yaw and roll bandwidth separation, and fast rudder rate. In other cases expensive modification to the steering gear will be required to achieve any significant roll reduction.

A disadvantage of RRS is that in major manoeuvres, demanding full rudder, the rudder roll system is cut out to devote full power to turning the ship, thus losing the stabilisation component. A further disadvantage is that, by definition, RRS is unable to correct steady state heel during turning manoeuvres.

Provided that the limitations are accepted the system offers some stabilization performance at low cost, without the addition of appendages and their associated noise. Most vessels do not have sufficient power in their steering gear to provide the fast rudder speed without modification, and the additional cost of increased rudder area is a further drawback. The cost to achieve the best rudder roll performance is of the same order as standard steering gear and fin stabilizers together.

In summary, to obtain satisfactory rudder roll stabilization from a standard steering gear with a rudder rate of 3 degrees/sec would entail:

- No increase in space
- 0.1 tonnes added weight
- Power increased to 90 KW for each of two pumps. (Approx 3 times power requirement for standard steering systems)

3.4 <u>Fin System</u>

The space, weight and power requirement for non-retractable fin stabilizers make the least impact on the vessel of any system. The performance and cost are acceptable to many navies borne out by the large numbers of installations world wide. A typical installation is shown in Figure 4.

To provide the desired moment for 3 degree VSC at 20 knots, two fins each of 4.25 sq m will be required. The requirements for the vessel are:

- $10m^3$ in the machinery spaces
- 14 tonnes added weight
- 40 KW electric power

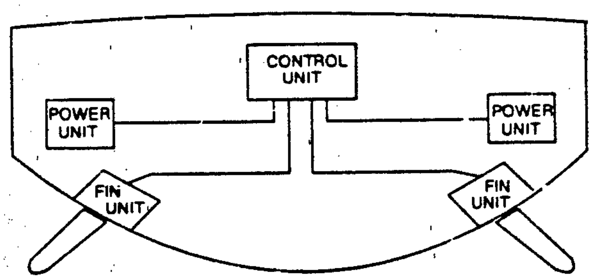


Figure 4 - Hull Section - Fin Stabilizer Block Diagram

The major disadvantage with all fin stabilizers is their dependence on ship's forward speed. They also generate hydrodynamic and mechanical noise, although reasonable precautions can be taken to minimise both these effects. Hydrodynamic noise can be reduced by operating at reduced fin angles, below the cavitation zone, and if operational reasons demanded the fins could be centred. Hydraulic noise can be reduced by use of electronic pressure control to ensure smooth transition on and off load.

A modern digital stabilizer controller, such as the Vosper Thornycroft Mk 5, brings several advantages over previous analogue systems. As a minimum requirement the controller needs to operate the prime movers to form a control function from measurements of the vessels and to position the fin surfaces.

Important benefits of a digital system arise from improved handling of surveillance and diagnostic information, which gives plain language warnings and automatic action decisions for more serious failures.

Maintenance and commissioning modes provide supporting facilities for changing parameters, clearing faults and setting up test routines. The control panel display assists the operator with menu driven instructions for maintenance and commissioning purposes.

The current generation of fin stabilizers, with well proven fin and hydraulic systems coupled to a digital controller, define the standard by which other systems are judged. Significant improvements in performance, at low ship speed, may be possible by development of other systems, but only at the expense of weight, space and power.

3.5 Rudder/Fin Integration System

The fin stabilizer has been established as the benchmark for performance by general acceptance. Its performance is speed dependent however, and for

reasons of economy of space, weight and power the systems installed are frequently performing below 3 degree WSC.

In this instance the benefits of integrated rudder/fin control may be used to provide additional capacity at moderate extra cost. A further benefit is the reduction of the unwanted rudder-roll and fin-yaw couplings. The rudder rate will have to be increased to provide acceptable rudder roll performance. A number of researchers are investigating the potential performance of an integrated system (Refs 1, 5).

The control system will be required to discriminate between course setting, course keeping and stabilization, with the need to provide safeguards for steering to take precedence over all other modes when required. The main benefit is likely to be limited to an improvement in roll damping at speeds below the optimum fin stabilizer design speed. The installed fin power will not be sufficient to correct listing during turns and the control system must be set to account for this condition.

Modern digital controllers are available and capable of combining current rudder roll and fin stabilization technologies, to provide a modest improvement in performance at little extra cost and minimal impact on the existing steering gear and fin stabilizers.

3.6 Small Waterplane Twin Hull Vessels

The SWATH concept is a most interesting challenge for the fin stabilizer and its control system.

The situation is unlike conventional monohull vessels, because pitch, roll and heave motions can be controlled by relatively small forces. Two pairs of fins are normally required and proven mechanical systems are already available at economic cost. The good sea keeping characteristics of the SWATH form mean that ship motions at low speed can be accepted without stabilizers.

SWATH vessels, by virtue of their low waterplane area, are particularly suited to motion control by fin stabilizers. In addition to roll damping, heave and pitch motions may be suppressed, thus creating an extremely stable platform with benefits for both military and commercial applications.

With regard to SWATH vessels, the Vosper Thornycroft Mk 5 digital stabilizer control system, as presented at the 8th Ships Control Symposium, Ref 6, has been further developed as a platform for execution of the advanced multivariable digital control algorithms associated with SWATH motion control. In addition to high speed execution of these algorithms, the system provides for constant health monitoring of itself, the input sensors, and the fin subsystems. Should a failure occur in one of these, the system automatically re-configures to provide the best stabilization using the remaining inputs and outputs. The facility to reconfigure following a failure is necessary because, unlike the monohull situation, a failure may cause significant disturbance to the vessel motion. The elimination of this possibility should endear operators to the SWATH concept.

4. CONCLUSIONS

The effective stabilizer systems available for conventional monohull vessels may be divided into two main groups:

- Active fins (this includes rudders)
- Active mass transfer

The major difference between the groups being that mass transfer systems require all their power from dedicated machinery, whereas fins develop the required stabilizing moment hydrodynamically and the majority of the power required is taken indirectly from the main propulsion. The input power for fin/rudder stabilizers is solely that required for positioning, and is much less than that required for pumping large quantities of water ballast. The moving weight solution offers the advantage of low power input, but this is coupled with the need for very high mechanical reliability which will require considerable investment during development.

The significant feature of both mass transfer systems is that they perform well at low ship speeds. However, this low speed performance must be of critical importance to the vessel operation, in order to justify the high cost in terms of weight, space and power (for the tank).

This returns our interest again to conventional fins, with the benefit of digital control.

Modern control capabilities and work on rudder roll systems have opened up the possibility of using rudders to enhance stabilizing performance. In this case the integration of rudder/fin motions to stabilization offer the prospect of performance improvement, which is now under investigation. Digital controllers will enable the systems to be automatically re-configured to suit all operational and manoeuvring requirements. This will increase the speed range at which rudder/fin stabilizers will perform effectively.

The digital system offers major advances in the presentation of surveillance and alarm information. Test and commissioning facilities can also be enhanced by providing dockside test functions allowing machinery to be run, test and tuned safely with the ship alongside. Software changes can be made economically to update the control system performance throughout the life of the equipment.

Fin stabilizers, or a combination of fins and rudders, with digital control currently offer the best technical and economical solutions. An effective roll stabilizer system which is independent of ship speed is a continuing requirement, however, present solutions demand too large a sacrifice of space, weight or power to provide practical solutions.

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